ECOLOGICAL AND RESOURCES CONSULTANTS LIMITED
508 CHARLOTTE STREET FREDERICTON, NEW BRUNSWICK, CANADA E3B 1M1 TEL. (506) 455-5278

FINAL REPORT

MAINTENANCE, CONSTRUCTION AND INSTALLATION OF AN ADDITIONAL SYSTEM, AND RESEARCH ON FURTHER IMPROVEMENTS AND EXTENDED APPLICATIONS OF THE SUBSIDENCE MONITORING AND TELEMETRY SYSTEM

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Ecological and Resources Consultants Ltd.
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E3B 1M2

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MICROMEDIA

PREFACE

This is the final report for Contract No. OSQ82-00051, covering maintenance, construction of an additional system, and research on further improvements and extended applications of the subsidence monitoring and telemetry system, submitted to CANMET, Mining Research Laboratories, Western Office, Department of Energy, Mines and Resources, Calgary, Alberta.

It also covers the work carried out under Contract No. OSQ80-00033, dealing with photogrammetric subsidence monitoring in conjunction with the above mentioned system.

As evident from the title, this project required expertise in several technical disciplines. Thus the responsibilities were shared among four key consultants of Ecological and Resources Consultants Ltd. in Fredericton, N.B., each dealing primarily with the aspects most suited for his technical experience.

Other technical and general support was provided as needed.

Fredericton, N.B.
1983-11-30

Ecological & Resources
Consultants Ltd.

Dr. A. Chrzanowski, P.Eng.
Project Director and Consultant on
Mining and Engineering Surveying

Dr. W. Faig, P.Eng.

Project Manager and Consultant on
Mining and Engineering Surveying
and Photogrammetry

Dr. B.J. Kurz

Consultant on Communication
Electronics and Systems Design

A. Makosinski

Consultant on Electronic Circuitry
and Components

ABSTRACT

As a follow-up to the development, installation and operation of a telemetry system for monitoring ground subsidence at a mining area near Sparwood, B.C., this report deals with its evaluation, maintenance and upgrading, an expansion of the system, as well as utilization of photogrammetry for subsidence monitoring, and research into the telemetry system and subsidence prediction.

Although the system has been operating extremely well, a number of steps were taken to further improve its performance (e.g., exchange of transceiver units). Regular maintenance and evaluation of the tilt readings was carried out as well.

Based on the experiences gained, the system was extended, and three new slaves were designed, constructed and tested. They are ready for installation on site.

Research into the telemetry system focussed on the design and construction of a new Master station, incorporating remote control access (by telephone) and alarm features, while remaining compatible with all the Slave stations.

Tiltmeter testing and calibration, including instruments which had been operational under adverse climatic conditions for several years, provided much needed insight into their performance characteristics.

The utilization of photogrammetry for subsidence monitoring under the extreme topographical and environmental conditions of the test site has been thoroughly investigated and provided results which are extremely useful. Furthermore, an attempt has been made to integrate the different approaches for the determination of ground subsidence, again with very good results.

After thoroughly investigating various prediction theories, the utilization of the finite element method for subsidence prediction modelling proved to be most useful and provided excellent results.

ACKNOWLEDGEMENTS

The Consultants wish to acknowledge with thanks the efforts of the following persons whose contributions were invaluable for the success of this project:

-- Members of the Scientific Authority in Calgary, especially Dr. Y.M. Fisekci, who was extremely supportive throughout the project, far in excess of his duties.

-- Messers. J. Secord, P. Romero and C. Armenakis of the University of New Brunswick, who carried out testing and evaluations as well as Dr. Z. Kolenda (Technical University of Mining, Krakow, Poland) and Mr. T. Fiedler (Zagreb University, Yugoslavia) who - while visiting at the University of New Brunswick - made valuable contributions to this project.

-- Mrs. Anna Szostak-Chrzanowski, who made her Finite Element Programme available and spent many hours on modelling the ground subsidence.

-- Mssers. R. Postlethweite, I. Berzins and C. DePaoli from Westar Mining Ltd. who provided continuous cooperation in collecting survey data.

-- Last but not least, the Consultants would like to thank Mr. G. Larocque of CANMET for his many hours spent helping and assisting in the field work and technical aspects of the project.

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1. INTRODUCTION

This report presents the results of the project entitled "Maintenance, Construction and Installation of an Additional System, and Research on Further Improvements and Extended Applications of the Subsidence Monitoring and Telemetry System" undertaken at a coal mining area near Sparwood, B.C. This project was contracted to Ecological and Resources Consultants Ltd. in Fredericton (referred to as Consultants in this report) by CANMET, Mining Research Laboratories, Western Office in Calgary on June 25, 1982.

Furthermore, the results of another contract entitled "Experimental Application of Aerial Photogrammetry to Subsidence Monitoring in Mountain Terrain" (DSS File No. 18SQ.23440-8-9016-1) between the Consultants and CANMET are included as the two projects are directly connected.

1.1 Background and Previous Contracts

On November 30, 1980, the final report on the previous contract by the Consultants was submitted to CANMET. This report and the contract were entitled: "Development, Installation and Operation of a Subsidence Monitoring and Telemetry System" and covered the period from March 30, 1979. During this time, the Consultants developed, constructed and installed a telemetry system for subsidence monitoring.

The system is based on measuring ground tilts with electronic tiltmeters at selected points above the mining exploitation. These tilts are then transduced into electrical signals which in turn are converted into radio frequency signals and transmitted to a master receiver unit. The recorded tilt changes can be translated into elevation differences.

The system, consisting of 5 field stations and a master controller, was installed in the area of the B.C. Coal (presently Westar Mining Ltd.) operations near Sparwood, B.C. in August 1980. Each field station consisted of a bi-axial tiltmeter and a slave station complete with radio transceiver and battery power supply. The master station with power supply hook-up, electronic mini-computer and radio transceiver was installed in an accessible location with power supply from the mine.

Figure 1.1 illustrates the locations of the five field stations at the test site above the coal extraction of sub-panel 06-100. The telemetry system was tested in the area for a period of over two years. One should emphasize that the main purpose of the test period was not to monitor the ground subsidence (this would require more than five tiltmeters) but to test the performance of the prototype system in the difficult climatic and topographical conditions and to test its potential capability to be included as part of an integrated survey scheme for subsidence monitoring in the future.

1.2 Performance of the Original System

Although the above mentioned contract expired in November 1980, the Scientific Authority (CANMET) had established an acceptance criterion, stating that the system has to be capable of continuous operation with no more than one sensor non-operational, over the period of one year from the date of acceptance. This basically meant, that the system had to continue to properly function through the winter 1980/81 until the monitoring area was again accessible in the summer of 1981.

Station #0 developed problems early in this first winter and ceased to respond to interrogation from the Master Station. All other

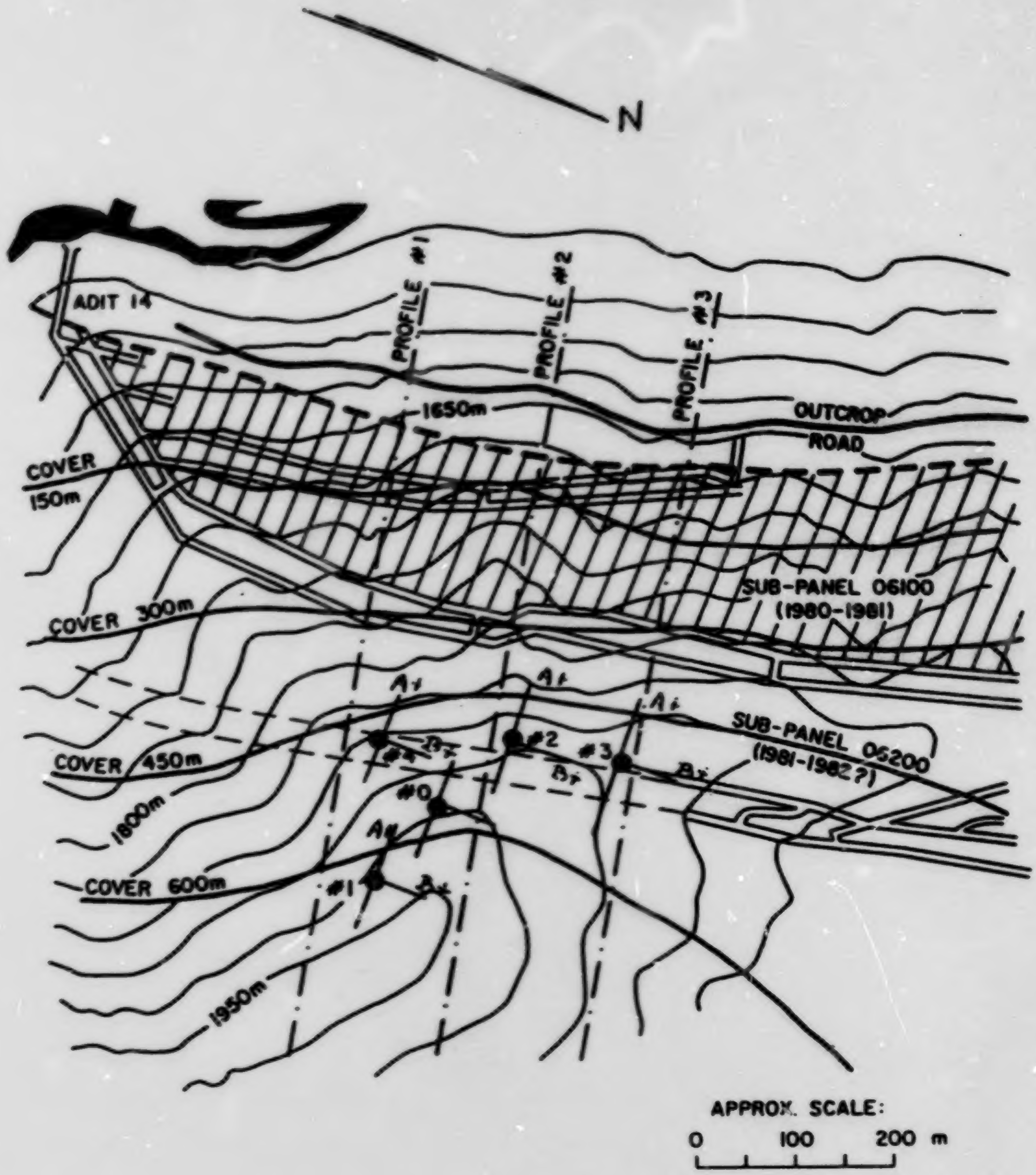


Fig. 1.1 Locations of the Field Stations of the Telemetry System.

stations worked properly, although occasionally one would not respond at the time but would again properly respond at a subsequent day of interrogations. A field check by members of CANMET and B.C. Coal in June 1981 revealed that the antenna of station #2 had been vandalized, presumably by a bear. It was replaced by the consultants during their maintenance visit in August 1981. The station #0 indicated problems with one sensor of the bi-axial tiltmeter. The whole station was returned to the Consultants for repairs and it was reinstalled (without the tiltmeter) on site in August 1982. All other stations were serviced which included resetting of the tiltmeters and re-charging of the batteries. All four stations continued to operate properly and to provide valuable data well into the period of the contract at hand with the last tilt readings taken in August 1983.

After these excellent experiences, it was decided to not only maintain the system, but to expand it, which led to the present contract.

1.3 Statement of Work

Based on a proposal submitted by the Consultants in March 1982, the new contract consisted originally of three major parts:

1) Maintenance and upgrading of the existing telemetry system;
2) Expansion of the system by five new field stations;
3) Research on further improvements and interpretation.

The following statement of work was attached to the contract:

The work will be carried out during FY 1982/83 and 1983/84 and the contractor shall:

1. a) Provide maintenance of the installed system over the hydraulic mine.
   b) Exchange of transceivers (from Motorolas to REPCO) to improve the reliability.

2. a) Investigate the expansion of the subsidence monitoring area beyond the mountain ridge in Sparwood with one of the two alternatives stated below:
   - i) to use a modified version of the present master station and a relay station on the ridge.
   - ii) to use another master station to control the slaves beyond the ridge (with 5 slaves and 5 bi-axial tiltmeters).
3. Conduct research on the following:
   - a) Additional testing of new types of tiltmeters in order to select the optimal model for future telemetry systems.
   - b) Inclusion of extended data analysis capability at the master station.
   - c) Development of a new mode of operation for the monitoring system where each slave itself could alarm the master about an unusual event concerning the data being sensed, (e.g., excessive methane contents, excessive tilt, etc.).
   - d) Implementation and operation of the access to the public telephone network for remote data acquisition purposes.
   - e) Long term in-house testing of individual units of the system for its enhanced reliability.
   - f) Investigation on the interpretation and integration of the monitored ground movement including a feasibility study on the prediction theory for the ground subsidence.

1.4 Changes to the Contract: Their Causes and Effects

Due to the fact that the contract was not signed until the end of June 1982, some of the originally planned tasks had to be rescheduled because of the extremely short working season on site with only a few snow-free months. Thus the exchange of the transceivers had to be postponed for one year. Furthermore, the Scientific Authority requested that initially only three new slave stations were to be built using tiltmeters. It was planned to equip the remaining two new slave stations with sensors other than tiltmeters to monitor other mining conditions at the adits.

Dr. Fisekci, the Scientific Authority, visited the Consultants on December 18, 1982 and proposed a number of changes to the contract. These were caused by changes in mining priorities on site, which in turn has led to different Research and Development needs for CANMET.

Thus the following changes were agreed to in December 1982, and formally recognized by Supply and Services Canada on July 28, 1982:

1) Delete section 2 on the "investigation into expansion beyond mountain ridge" as of December 31, 1982 and meet the requirements of payments for labour and materials committed to the date of December 31, 1982.

2) Complete the entire R&D work on subsidence telemetry and aerial photogrammetry by December 31, 1983 with final reports for presentations in seminars in Calgary and Ottawa.

3) Continue R&D work in section 1 and 3 dealing with maintenance and R&D to upgrade the telemetry system for completion by December 31, 1983, including the preparation of three slave stations for the three tiltmeters.

During reconnaissance (see section 4.8) for the installation of the three new slaves it became apparent that Westar Mining Ltd. is now interested in monitoring the north-east slope of the Sparwood Ridge ("behind the ridge"). However, they would prefer to have the installation postponed until the summer 1984 thus being freed from the responsibility of maintaining the telemetry system during the winter.

Their decision is based on the fact that due to a delay in the development work for sub-panel 6-200, no significant ground movement on the northeast slope is expected before the end of 1984.

Therefore, the following decisions were made in August 1983:

a) postpone the installation of the telemetry system near Sparwood until August 1984;

b) Immediately dismantle the original system and ship it to the Consultants for additional research on its behaviour.

Dr. Fisekci, the Scientific Authority, suggested, that the present contract should not extend beyond December 1983, but mentioned that the money which is saved due to the cancellation of the installation be allocated within a new contract for the installation only. Thus this report covers all aspects of the contract except for the installation of the new slaves.

2. MAINTENANCE AND UPGRADING OF THE EXISTING TELEMETRY SYSTEM

The upgrade of the existing telemetry system affects the Master station, all five slave stations and the external tiltmeter connection to the slaves. All upgrades are of a hardware nature only without affecting the operation of the system at all. In the sequel, the existing telemetry system components (as described in the Final Report 1980) are denoted Vers 1, whereas the upgraded system components are denoted Vers 1.1.

2.1 Objectives

The upgrade of the existing telemetry system is to improve the reliability of the wireless radio-based data transmission links and to enhance the capabilities of the Master station. In addition, field service of the external tiltmeters is facilitated.

Prime concern was given to maintaining full compatibility between the Vers 1 and the Vers 1.1 system components. Any slave version can be used with any Master version as no operational functions are incompatible.

2.2 Upgrading of Slave Stations

The VHF-radio link of the Vers 1 system was shown to be the most problem prone part. The high failure rate of the Motorola HT 210 transceivers was clearly pointed out in the Final Report 1980. It was decided to replace these tranceivers with modern VHF transmitter/receiver modules manufactured by REPCO. Two antennas are being used (one for transmit, one for receive) to avoid antenna switching relays which can be additional sources of VHF problems.

The power switching relay which supplies power to either the transmitter or receiver, is mounted on the slave's electronic board away from the transmitter's VHF-contaminated area to avoid latch-up due to excessive signal reflection in adverse climate conditions (snow partly covering antennas).

A pre-detection filter in form of a bandpass is inserted between the receiver and the TLM module to clean up received modulated signals from unwanted harmonic distortions, thus noticeably improving the reliability of the data transmission under adverse conditions.

The above upgrade to the system's radio-based data communication link is illustrated in Figures 2.1 through 2.3. Figure 2.1 shows the new REPCO Transmitter and Receiver modules in separate housings. Changes in the telemetry module, shown in Figure 2.3, affect the squelch detection (T32), the power switching relay (Rel 31), the pre-detection filter (IC 34) with its zero-crossing detector (IC 32) which is adjustable for the required (50±3)% duty cycle of its output signal. The frequency response of the pre-detection bandpass is shown in Figure 2.2, indicating the filtering of the two FSK frequencies (1070 Hz, 1270 Hz) with their sidebands. In order to achieve best signal conditioning by this filter, the bit rate for the serial data communication is reduced to 150 baud, thus generating fewer significant sidebands and allowing for a narrower filter response.

Another upgrade affects the power distribution unit PDU. The relay powering the data acquisition module, when instructed by the microprocessor, is removed. The DAQM module is powered from the microprocessor module MPCU. This change was necessitated by the need for the transmitter/receiver power switching relay (Rel 31) which is located on the slave's electronic board in place of the DAQM power-up relay. A slightly

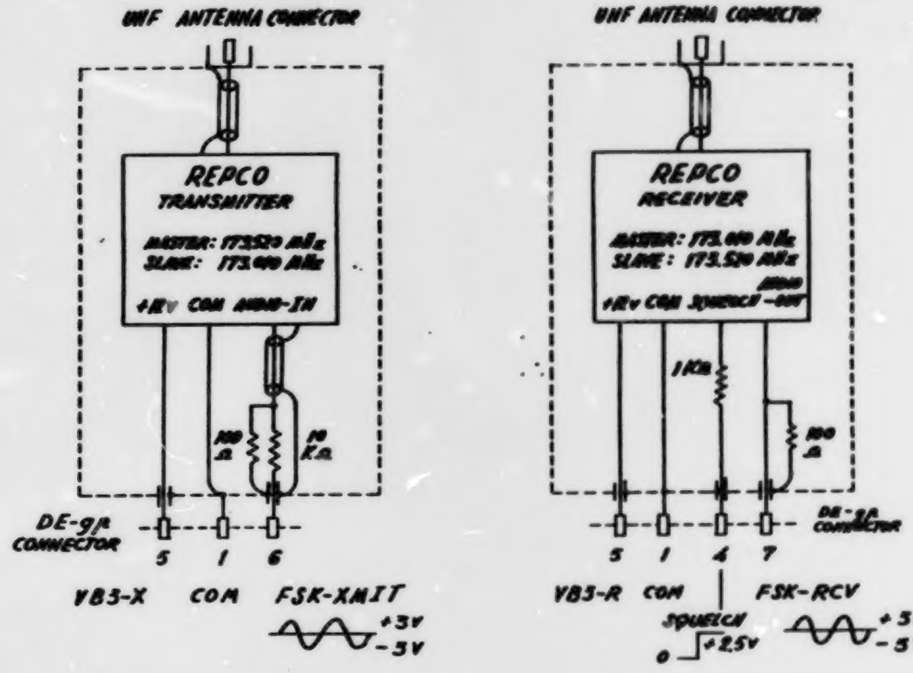


Fig. 2.1: VHF Transmitter and Receiver Modules (Slave Vers 1.1).

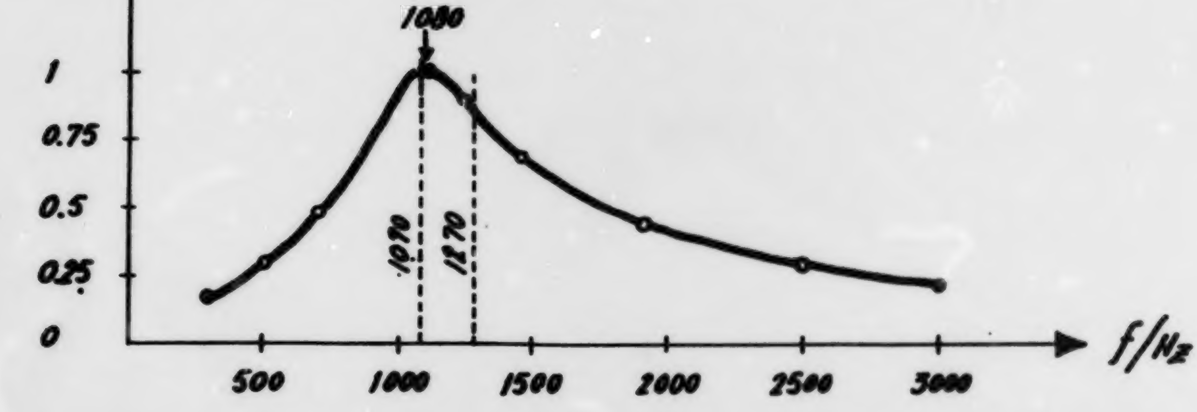


Fig. 2.2: Frequency Response of the Pre-Detection Filter (Slave Vers 1.1).

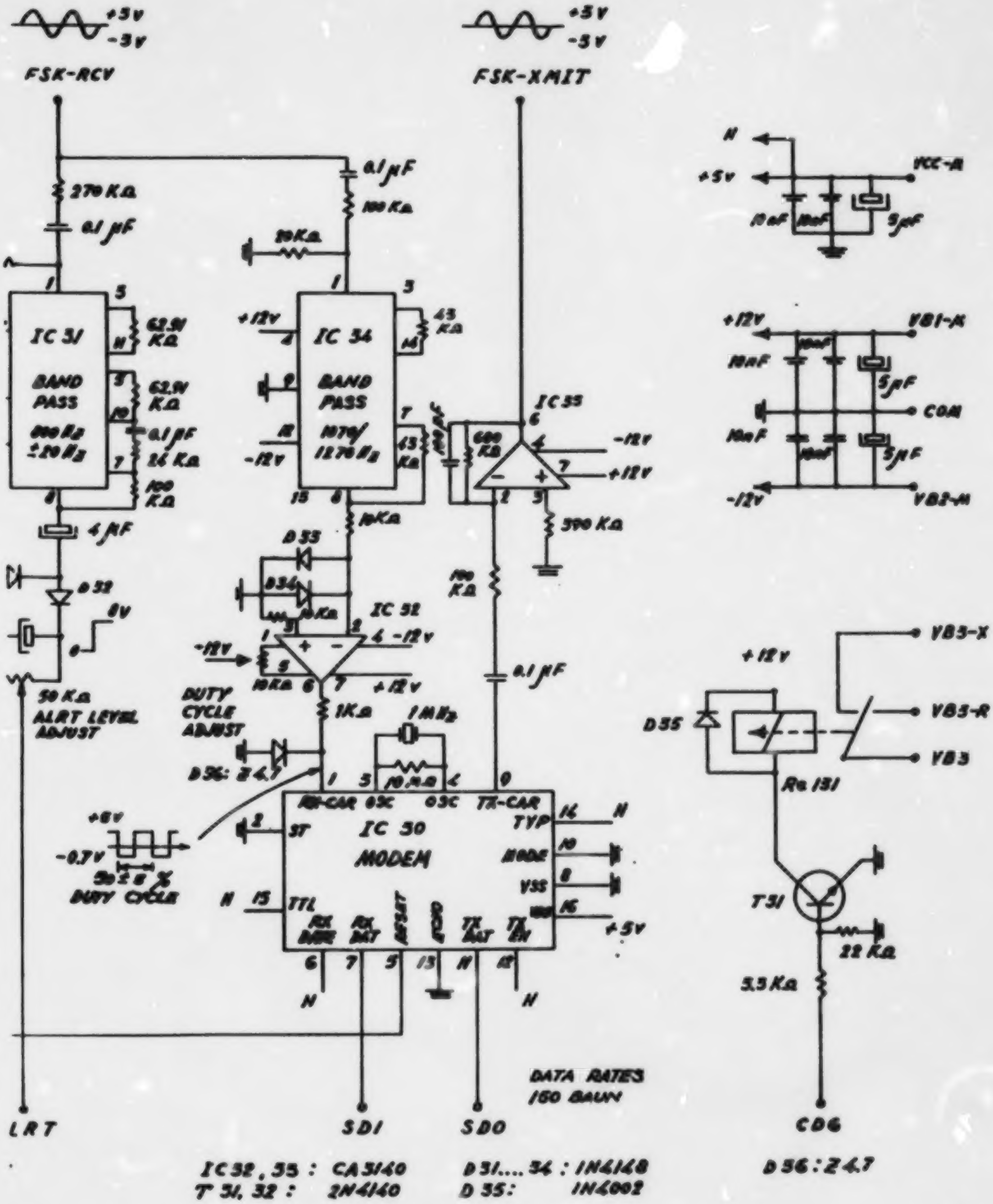


Fig. 2.3: Telemetry Module TLM (Slave Vers 1.1).

higher (+15%) energy consumption of the DAQM is the result which is tolerable.

The time-out condition of the slave is modified which affects the automatic return to the stand-by mode after an interrogation by the Master. The slave returns to stand-by immediately after the detection of a transmitted slave address which is not its home address. This method shortens the power-up interval of non-addressed slaves considerably (from 8 to 3 sec) and leads to an overall reduction of the slaves' battery power consumption, more than compensating for the increse in DAQM power needs.

The tiltmeters which are located external to the slave's steel housing are now connected to the slave via a sealed set of connectors (see section 4.2). This permits ready removal of the tiltmeter from the slave, for maintenance purposes. The interconnection scheme is illustrated in Figure 2.4. No changes are made to either the dual preamplifiers or the wiring harness.

The incorporation of the REPCO VHF transmitter/receiver devices and the slightly increased energy consumption of the DAQM unit affects the estimate of the expected battery lifetime per slave. The equations in Section 4.6 of the previous Final Report have been revised assuming a summer/winter operation of 8/4 months, respectively, with temperatures of $20^{\circ}C/-25^{\circ}C$ during these periods respectively. The predicted slave battery lifetime in terms of k full scans of N slaves a day, is plotted in Figure 2.5.

2.3 Maintenance

A thorough maintenance of the original telemetry system was carried out on site at the end of August 1982.

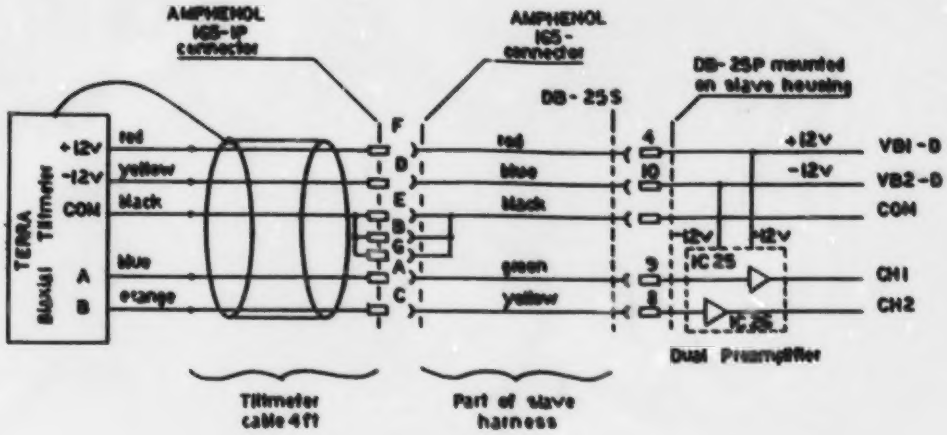


Fig. 2.4: Tiltmeter Connection Scheme (Slave Vers 1.1).

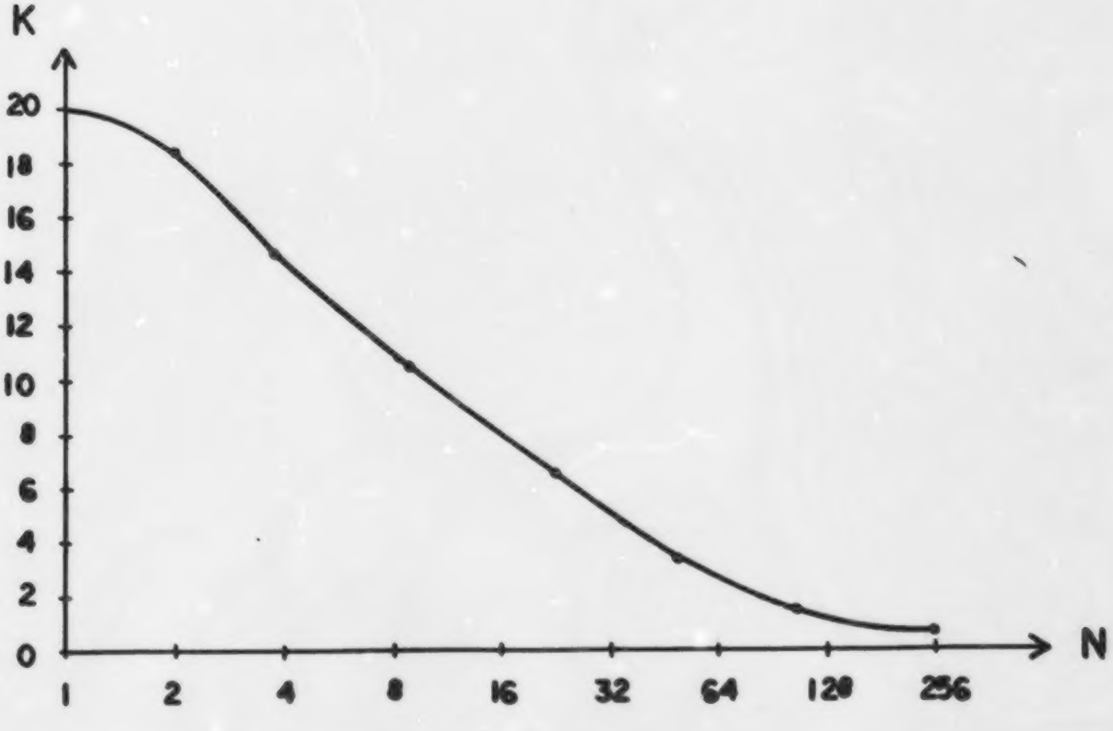


Fig. 2.5: Estimated Battery Lifetime in terms of k (full scans/day) versus N (Slave in system); excluding receiver and transmitter power.

All Slave stations were tested manually for proper functioning using the test plug (start-up and time-out). The Alert-M level was adjusted to ~ 4V upon call by Master. The transceivers' volume and squelch (threshold -1/16 turn) were reset and the transmit frequencies readjusted. The response to remote calls was tested for proper operation.

All Slave housings were cleaned and the battery terminals decorroded and protected with vaseline. All battery wires were checked for breakage of strands and resoldered when necessary.

The manually recorded data was compared with the printout on the Master and the conversion factors for the tiltmeter readings (gains) and the battery test voltages were updated. The field strengths at the Master station were measured for each Slave transmission.

The following list indicates additional actions taken for each telemetry unit:

Slave 0: Relocated at top of the mountain; Electronic unit, which was repaired in Fredericton (defective ADC) was installed. First day's test OK, then ceased responding. Simply reconnecting the 25-pin harness connector solved the problem (bad contacts are assumed). Uses tranceiver #0.

Slave 1: Initially no response; this was diagnosed as failure of transceiver #1 which did not transmit, although driven properly by MPCU. Corroded on/off switch was the problem: jumped. Test now without problems. Uses transceiver #1.

Slave 2: No problems. Uses transceiver #2.

Slave 3: Transmission errors detected and not recovered about 50% of time: transceiver #3 latched up. Readjusted antenna cable (shorten ~ 30 cm) solves this problem. Reduced Alert-level from ~6 to ~4V. Now operating correctly. Uses transceiver #3.

Slave 4: Occasional time-out detected, but retry always successful. Pinpointed to problem with Slave 3 which latched up for ~ 1 min. when Slave 4 was sending for the first time. After Slave 3 was repaired, Slave 4 was OK. Reduced Alert-M level to ~ 4V. Uses transceiver #6.

More slave data:

Slave	0	1	2	3	4	Master	
Field strength	250	100	150	5.10	300	--	V
Transmission Frequency		173.0100				173.5211	MHz
Alert-M level	4.5	4.3		4	4.1	--	V

The system was run under automatic full-scan call at 10 min. intervals for 1 1/2 hours. All stations came in clear. Only one successful retransmit of Slave 3 was detected (lowest field strength: so most sensitive to noise).

The updated gains for the tiltmeter and the battery test voltages are given in Table 2.1.

Table 2.1

Updated gains for tiltmeter channels A and B, and for battery test channels as of 1 September, 1982:

	tiltmeter @ 25°C					
Slave	A	B	CH4 +VB1	CH5 -VB2	CH6 +VB3	
0						tiltmeter gains extrapolated to +25°C
1	-5.66	-5.65	3.06	3.03	2.90	
2	-5.73	-5.24	3.05	3.05	3.06	
3	-6.05	-6.07	3.05	3.02	3.03	
4	-5.59	-5.66	3.02	3.01	3.02	

2.4 Evaluation of Tiltmeters and Tilt Results

The evaluation covers the period between October 12, 1980 when the system became fully operational and August 30, 1983 when the last tilt readings were taken before dismantling of the field stations. During the three year period, forty-one sets of readings from field stations #1, #2, #3 and #4 were processed. This comparatively small number of available readings was due to frequent failure of the power supply from the mine to the Master Station, temporary blockages (land- and snow slides) of the access road to the Master Station, and shortage of personnel to make frequent visits to the station. The power failures did not allow for a fully automatic mode of operation. As already mentioned, the tiltmeter No. 105 of the field station #0 was malfunctioning soon after commencing the operation. The tiltmeter was removed from the site during the summer of 1981 and was sent back to the manufacturer (Terra Technology) in the United

States. The tiltmeter has been repaired but it has not been reinstalled in Sparwood due to the aforementioned transmission problems which had developed at the slave #0. The tiltmeter will be used in the new expanded telemetry system (see section 4).

All remaining four tiltmeters worked very well through the entire test period.

The tiltmeters used in the test have a maximum tilt range of ± 6°, corresponding to an output voltage range of ± 5V. In order to reduce the range of the tiltmeters to about ± 1° as it was required for the project, an amplification of the signal with the gain of approximately 6x had to be applied at the slave stations. The gain may slightly change with time. During the maintenance visit in August 1982, the gains were checked and compared with the original values giving the following results extrapolated to the temperature +25°C (the values in the brackets are the old ones):

Slave	Tiltmeter gains:	
No.	Axis A	Axis B
1	-5.66	-5.65
	(-5.60)	(-5.67)
2	-5.73	-5.24
	(-6.09)	(-5.67)
3	-6.05	-6.07
	(-6.35)	(-5.99)
4	-5.59	-5.66
	(-5.82)	(-5.96)

The updated gains have been used in the tilt calculations commencing September 1, 1982. The corrected formulae for the tilt calculations are listed below:

Stn. #1:
Tiltmeter No. 101

$$\alpha''_A = \frac{r_A - T + 25}{-1.348 - 0.00029T}(1 + \epsilon) + 3.36T$$

$$\alpha''_B = \frac{r_B - T + 25}{-1.370 - 0.00029T}(1 + \epsilon) + 0.37T$$

Stn. #2:
Tiltmeter No. 106

$$\alpha''_A = \frac{r_A - 0.91T + 23}{-1.404 - 0.00046T}(1 + \epsilon) + 3.95T$$

$$\alpha''_B = \frac{r_B - 0.91T + 23}{-1.303 - 0.00046T}(1 + \epsilon) + 0.70T$$

Stn. #3:
Tiltmeter No. 103

$$\alpha''_A = \frac{r_A - 0.80T + 20}{-1.533 - 0.00029T}(1 + \epsilon) + 0.75T$$

$$\alpha''_B = \frac{r_B - 0.80T + 20}{-1.448 - 0.00029T}(1 + \epsilon) + 3.51T$$

Stn. #4:
Tiltmeter No. 104

$$\alpha''_A = \frac{r_A - T + 25}{-1.331 - 0.00071T}(1 + \epsilon) + 1.70T$$

$$\alpha''_B = \frac{r_B - T + 25}{-1.368 - 0.00071T}(1 + \epsilon) + 3.88T$$

where:

r_A and r_B are tilt readouts at the Master Station in [mV];

T: temperature in $^{\circ}$C;

ϵ: coefficient due to change in the voltage of the power supply (ϵ=0 if the voltage of the batteries does not drop more than -10% of the initial voltage).

A full explanation and derivation of the formulae was given in the previous Final Report (sections 5 and 7.2).

Table 2.2 lists calculated tilts between October 12, 1980 and August 30, 1983. The readings of the tiltmeters at station #2 had to be reset to zero on August 28, 1981 because there was the suspicion that the tiltmeter was disturbed when the antenna of the slave unit was broken off earlier that year. Therefore, the tilts at station #2 show a discontinuity in 1981. The last tilt readings were taken manually on August 30, 1983 because the Master Station and the slave units had been dismantled earlier and shipped to Fredericton. At the time of the manual readings it was discovered, that the tiltmeter No. 103 at station #3 had been broken off its base plate and thrown on the ground. There has been no explanation whether it was an act by wild game or of human vandalism. The tiltmeter was taken to Fredericton for a check-up.

The total tilts from Table 2.2 have been plotted in Fig. 2.6. The graphical display of the tilts gives a good picture of the time-dependent behaviour of the surface during the extraction of sub-panel 06-100. Some of the sudden "kinks" in the tilt graphs have been verified by underground bumps recorded at the same time. The other irregularities have, perhaps, been sudden collapses of rock masses which went unnoticed in the extraction area.

One can also see from the graph, that the major subsidence took place over a period of only about 5 months. The time dependent correlation between the underground extraction progress and its influence on the surface can easily be derived from the tilt records. The picture would be, of course, more useful if the tilt readings would have been taken more frequently and at more locations. However, as it has already been mentioned, the recorded tilts of the few field stations during the test period were not meant to be used for an interpretation of the mining

(Note: the azimuth of the total tilts is calculated
in respect to the directions of A+ axes)

Date	Station #1			Station #2			Station #3			Station #4		
	A+	B+	Total tilts	A+	B+	Total tilts	A+	B+	Total tilts	A+	B+	Total tilts
12.10 1960	([illegible]) 0"	([illegible]) 0"	0" 0°	([illegible]) 0"	([illegible]) 0"	0" 0°	(-50) 0"	(+100) 0"	0" 0°	(100) 0"	(-80) 0"	0" 0°
24.10	-6	-45	[illegible]	-4	+10	-11" -46°	—	—		-3	+13	-13 -77°
26.10	-6	-46	[illegible]	-6	+9	-11" -35°	—	—		-2	+16	-16 -83°
6.11	-10	-30	-41" +10°	-11	+17	-20" -57°	—	—		-19	+41	-45" -65°
10.11	-3	-45	-45" -85°	+30	-20	+36" -36°	—	—		-34	+12	-36" -19°
13.11	0	-40	-40" -90°	+20	+6	+20" +16°	—	—		-12	+95	95" -75°
18.11	-11	-47	-48" +77°	-96	+7	-96" -5°	—	—		-4	+40	-41 -84°
20.01 1961	-90	-100	-135" +45°	-195	-46	-190" +14°	-54	-43	-69" +38°	+37	+24	+44" +32°
12.02	-105	-111	[illegible] +37°	-200	+31	-202" -6°	-52	-7	-52" +8°	-13	-10	-16" +38°
13.02	-172	-133	-211" +38°	-279	+6	-279" -1°	-74	-2	-74" +2°	-6	-21	-22" +74°
16.02	-177	-134	[illegible] +37°	-290	+6	-290" -1°	-96	+42	-107" -23°	+7	+20	+21" +70°
25.02	-177	-134	[illegible] +37°	-319	+6	-319" -1°	—	—		-30	-4	-30" -8°
10.03	-170	-136	[illegible] +37°	-322	+5	-322 -1°	—	—		—	—	
18.03	—	—		—	—		-140	+25	-142" -10°	-80	+17	-82" -12°
9.04	-293	-106	[illegible] +20°	-334	+5	-334 -1°	—	—		—	—	
21.04	-310	-180	[illegible] +30°	—	—		—	—		—	—	
27.04	-330	-131	[illegible] +30°	-405	-16	-405 +2°	—	—		-254	-80	-270 +18°
30.04	-350	-144	[illegible] +27°	-495	-6	-495 +1°	—	—		-275	-110	-296 +22°
19.05	-382	-231	[illegible] +31°	-600	-7	-600 0°	-1050	+252	-1080 -13°	-300	-211	[illegible] +35°
25.05	-402	[illegible]	[illegible] +31	[illegible]	-6	[illegible] 0°	-1330	+350	-1385 -15°	-450	-300	-530 +33°
10.06	-770	-430	[illegible] +30°	—	—		—	—		—	—	
27.06	-1507 (New reference)	-575	-1614		Discontinued reading		-2310 (New reference)	+1100	-2560 -26°	-1125 (New reference)	-855	-1413 +37°
28.06	-1507	-575	-1614 21°	0"	0"	0" 0°	-2310	+1100	-2560 -26°	-1125	-855	-1413 +37°
9.08	-1547	-600	-1660 +21°	-30	-31	-43 -46°	-2315	+1129	-2575 -26°	-1134	-865	-1426 +37°
21.08	-1624	-657	-1752 22°	-63	+41	-75 -33°	-2270	+1134	-2537 -27°	-1202	-873	-1486 +36°
30.08	-1647	-657	-1773 +22°	-78	+46	-91 -30°	-2284	+1158	-2560 -27°	-1230	-838	-1488 +34°
1.10	-1700	-657	-1823 +21°	-235	+27	-237 -6°	-2299	+1221	-2595 -28°	-1301	-878	-1638 +34°
18.12	-1807	-673	-1927 +20°	-305	+30	-306 -6°	-2297	+1290	-2630 -29°	-1411	-900	-1673 +33°
11.01 1962	-1807	-660	[illegible] +19°	-272	+20	-273 -4°	-2338	+1277	-2663 -29°	-1377	-824	-1604 +31°
04.02	-1854	-691	[illegible] +19°	-300	+40	-305 -7°	—	—		-1326	-821	-1612 +30°
20.02	-1993	-680	[illegible] +19°	-415	+32	-416 -4°	-2392	+1305	-2725 -29°	-1314	-949	-1621 +36°
5.04	[illegible]	-716	[illegible] +21°	-305	-40	[illegible] +8°	—	—		-1436	-995	-1735 +35°
7.05	-1987	-716	[illegible] +20°	-463	+52	-466 -6°	—	—		-1448	-970	-1743 +34°
12.06	-1917	-765	[illegible] +22°	-386	-101	-399 +15°	-2461	+1277	-2773 -27°	-1418	-985	-1711 +35°
10.08	-1917	-723	[illegible] +21°	—	—	—	-2527	+1257	-2822 -26°	-1426	-1011	-1750 +35°
1.09	-2077	-754	[illegible] +20°	[illegible]	-274	[illegible] +44°	-2580	+1246	-2873 -26°	-1474	-1165	-1880 +37°
30.11	-2094	[illegible]	[illegible] +21°	-207	[illegible]	[illegible] +30°	-2570	+1239	-2853 -25°	-1175	-1120	[illegible]
11.12 1962	[illegible]	-770	[illegible] +21°	[illegible]	[illegible]	[illegible]	-2575	+1395	-2928 -28°	-1487	-1149	-1879 +38°
12.03 1963	-2074	[illegible]	[illegible]	[illegible]	-237	[illegible] +51°	-2651	+1410	-3003 -28°	-1440	-1075	[illegible]
20.05 1963	-2013	[illegible]	[illegible] +17°	-162	[illegible]	-213 +77°		Tiltmeter destroyed		-1421	-1080	[illegible] +37°

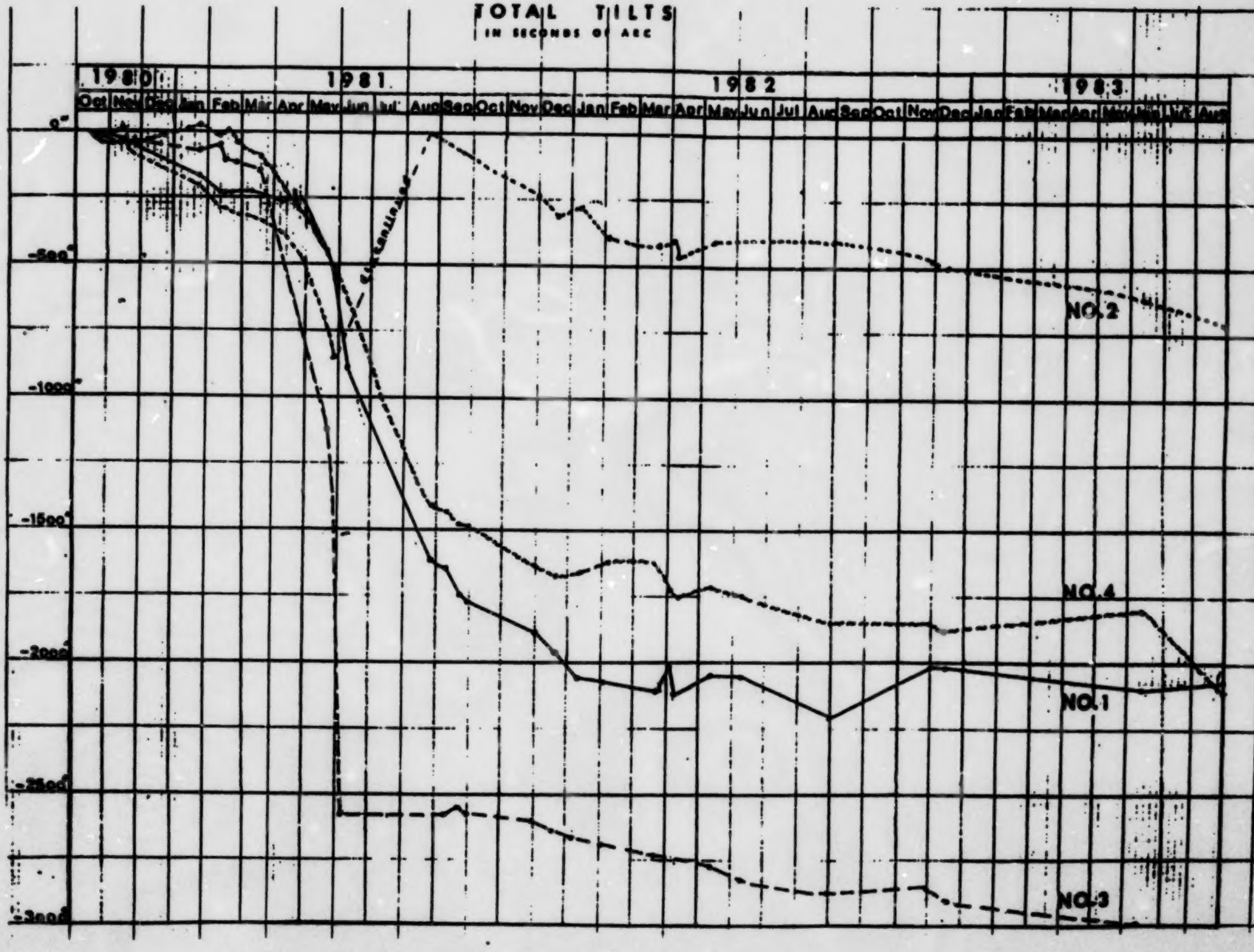


Fig. 2.6 Total Tilts in Seconds of Arc.

subsidence but only for the purpose of testing the telemetry system.

Some additional remarks on the use of tiltmeters in monitoring the mining subsidence are given in section 6.4.

After the aforementioned dismantling of all field stations, all four tiltmeters were taken to Fredericton for testing and recalibration.

This test was anticipated with interest to see whether the tiltmeters have changed their characteristics after being exposed to the difficult climate conditions for such a long time.

As expected, tiltmeter No. 103 (field station No. 3), which had been broken off its base plate by an act of vandalism or by a bear, has shown a permanent damage to one of its sensors. The B-axis has not responded to anv tilts. The A-axis seemed to respond normally, but after some additional tests it has become clear that the sensor gives erratic results. Therefore, the tiltmeter must be sent to the manufacturer (Terra Technology) for repairs.

The remaining three tiltmeters have been checked for changes in their scale factors, using the calibrating system as described in the 1980 Final Report. The scale factors have been determined over the tilt-range of $\pm 2^{\circ}$ at intervals of 20 minutes of arc (Table 2.3). The final results, obtained through least squares fit, are presented in Table 2.3 and are compared with the original factors determined in 1980.

Table 2.3: Comparison of Scale Factors in mV/"

Tiltmeter	New Scale Factors		Old Scale Factors	
	Axis A	Axis B	Axis A	Axis B
#101	0.2412	0.2424	0.2408	0.2416
#104	0.2301	0.2312	0.2287	0.2296
#106	0.2313	0.2301	0.2306	0.2298

The maximum difference (#104, Axis B) reaches 0.0016 mV/" which corresponds to a maximum change of 26" (seconds of arc) over the maximum usable tilt of ± 1°. This value is within the design accuracy of the tilt determination.

The tiltmeters have also been subjected to a 20 days' drift test at constant temperatures in a laboratory of the University of New Brunswick. A new, more rigid calibration plate than the one described in the 1980 Final Report, has been used in the test. The calibration plate is equipped with two precision spirit levels which permit to cntrol the orientation of the plate in respect to the vertical with an accuracy of few seconds of arc. Photographs in Fig. 2.7 show the calibration set-up. The results oof the drift test are summarized in Fig. 2.8. All three tiltmeters exhibited very regular behaviour after a one day settling time. Sensors #104A, #106B and both sensors of tiltmeter #101 did not indicate any drift trend. Sensors #104B and #106A demonstrated a small drift of about 0.8"/day. However, it was discovered at a later date when testing the new tiltmeters (see section 4.5.3), that the minimum time required for a proper drift test is 60 days. Therefore, it is recommended to check the drift of the old tiltmeters again prior to their field installation.

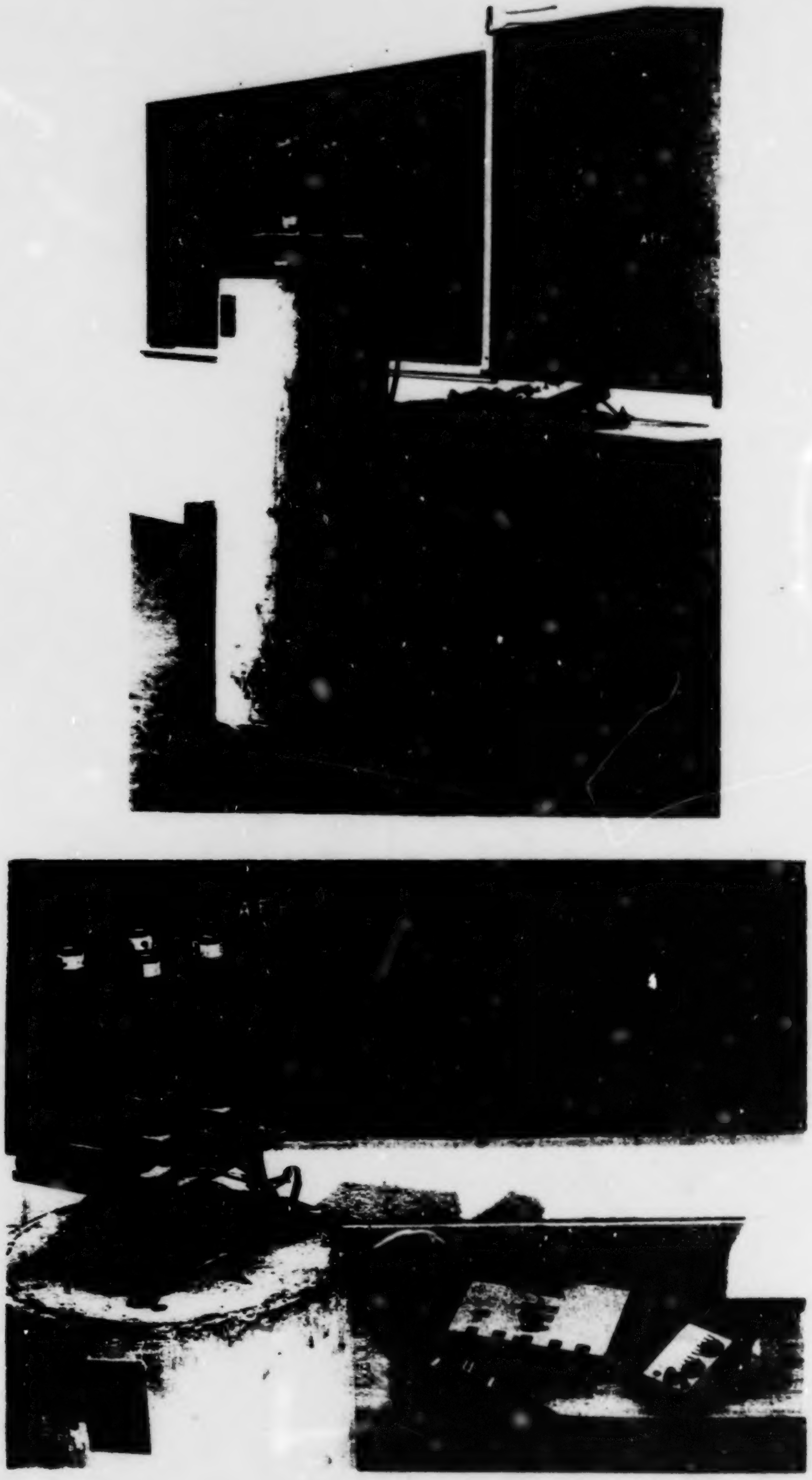


Fig. 2.7 Laboratory Set-up for the Tiltmeters Calibration.

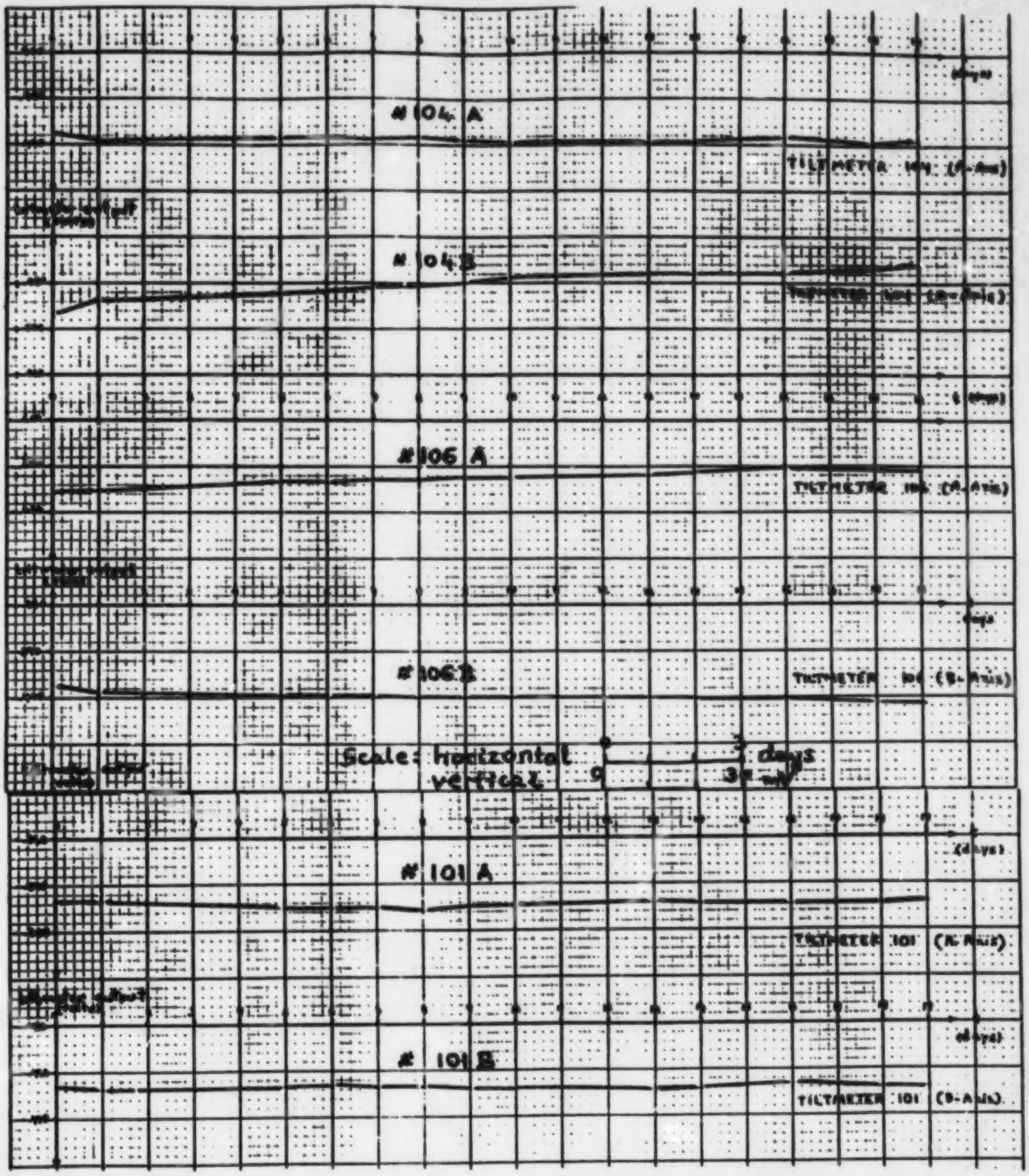


Fig. 2.8 Results of the Drift Test.

Generally, the Terra Technology tiltmeters have proven to be very reliable instruments for the purpose of deformation monitoring over a prolonged period of time in difficult climatic conditions. They are resistant to shocks and vibrations of normal transportation and shipment processes. However, one should remember that they are precision instruments which cannot be "hammered" and require a careful calibration.

3. UTILIZATION OF PHOTOGRAMMETRY

3.1 Background and Objectives

A small separate contract between the Consultants and CANMET, entitled "Experimental Applications of Aerial Photogrammetry to Subsidence Monitoring in Mountain Terrain" (DSS File No. 23440-8-9016-1) provided the impetus to expand the subsidence investigation by considering photogrammetry as a means of measuring geometric displacements.

Photography was flown during the summers 1980, 1981 and 1982. It was planned to use the 1980 photography as a standard against which the subsequent missions were to be compared in order to determine the subsidence in the area of interest. In conjunction with the evaluations, research was to be carried out investigating different photogrammetric approaches under these extreme topographic conditions. In addition, one set of infrared photography was flown in order to study its suitability for detecting cracks and subsurface features which are not visible in regular aerial photography.

3.2 1980 - Photography and Its Evaluation

In order to integrate tiltmeter readings, photogrammetry and ground surveying results, the study area was defined by ERCL personnel and Dr. Fisekci. Locations for ground control points were selected by optimizing within local constraints. Three targets were placed on top of the ridge, in spite of the fact that subsidence was expected to occur beyond the ridge. Accessibility for resurveys plus visibility being the main reasons for that.

With assistance from CANMET and Kaiser Resources (subsequently B.C. Coal and Westar Mining Ltd.), wooden targets (1.2 x 1.2 m^2) with painted crosses were positioned on top of the control points. The boxes at the tiltmeter stations and the top of the Master station were painted with a cross as well.

B.C. Coal's survey crew coordinated most of the points within the local mine-grid. However, due to limited time available before the closure of the mine, they were unable to include the new ridge points at that time.

A detailed planning for coverage in approximately 1:7000 was carried out. The flight parameters were discussed with the president of Orhan's Reproduction and Photomapping Ltd. in Calgary who carried out the photographic mission.

Since this flight was to serve as the standard against which subsequent flights were to be compared, a 1:2500 map with 5 m contours of the study area was prepared. This map included control points and tilt stations as well as terrain irregularities (holes, cracks).

3.3 1981 Photography and Its Evaluation

The actual subsidence determination was based on the 1981 photography. In the time span between the two photographic missions, mining operations had been carried out beneath the test area. In 1981 the area was also covered with infrared photography. As described in Report II, submitted on March 26, 1982 to CANMET, the following investigations were carried out:

A) Study of the suitability of infrared photography for detecting cracks and subsurface features not visible in regular photography.

Unfortunately, this type of coverage provided little additional information, other than some ideas on soil, humidity and vegetation - all unrelated to subsidence. As expected, no additional cracks were determined. In order to detect possible air temperature differences near cracks, a heat sensor would be required rather than photography that records reflected energy in the near infrared spectrum.

B) Phtogrammetric subsidence determination.

There were a few control related problems which greatly increased the work and reduced the accuracy. With the actual coverage being somewhat different from the planned, one of the control points below the exploitation area was not on the photograph. To compound this problem, the ridge points were not resurveyed, due to closure of the mine, thus making proper orientation of the photographs impossible.

Nevertheless, a fit of slightly better than 10 cm was finally achieved, using a least squared fit and identifiable ground points plus the tilt stations.

a) Contour comparison.

A new contour map was plotted from the 1981 photography. Comparison however revealed that the changes were not significantly large to justify this approach for further missions. Physical changes, i.e., new holes, were plotted onto this map.

b) Movement of physical objects.

Clearly identifiable points in both the 1980 and 1981 photography were measured with a precision comarator. The coordinate differences provided directly the movement components in the three coordinate directions. Although this approach is very useful and accurate, its application is limited because the number of clearly identifiable points is rather small.

c) Movements at mathematically defined points.

Based on the assumption that subsidence consists primarily of a vertical movement, as is the case for most conventional study areas, a digital terrain modelling approach was attempted. Utilizing the capabilities of the analytical plotter AP/2C, the given rectangular surveying grid was superimposed on the test area and grid points were measured at 50 m intervals. This was done for both years by automatically driving the measuring mark to a grid point where x/y coordinates were given and then reading the z value.

This type of measurement has been very successfully applied in open pit mining and for volume determination, as well as in subsidence areas on flat ground.

Although it provides elevation changes very accurately which can easily be used for area representation using digital mapping techniques, the results were not useful for the Sparwood test case. Discrepancies between the results obtained in this manner and the movement of physical objects were larger than the precision of the method suggested, especially since the absolute amounts of subsidence appeared to be smaller. This, together with the results of the contour comparison has to be attributed to the large component of horizontal movement. By using fixed plane metric positions, this fact is neglected, which leads to incorrect values.

This fact clearly shows, that methods which have been successfully applied in flat terrain cannot be transferred to areas with extreme topographical conditions, such as the Sparwood Ridge. Thus profiles were useless as well, since they suffer of the same deficiency.

d) Area evaluation using cross identification.

Thus subsidence can only properly be determined if the same surface points are measured in both (and subsequent) epochs. The lack of well identified ground points led to the development of a stereo - cross identification procedure, whereby the identification is obtained by using photography of both epochs together to form a limited stereoscopic image within which points are identified and later cross identified to other photographs of the corresponding mission, again using stereoscopic vision.

Once these points were available, the subsidence vectors could be obtained. A comparison with the field survey results showed agreement within a few centimetres.

3.4 The 1982 Photography and Its Evaluation

With the planned extension of the mining operations, subsidence well beyond the ridge was expected, and thus the photographic coverage was to be extended accordingly. This would provide new subsidence data on the previous study area as well as reference photography beyond Sparwood Ridge.

Based on the experiences from the 1980 and 1981 missions, the Consultants provided Dr. Fisekci with details for the 1982 mission, including photographs in whih locations for new and existing targets were plotted. In order to avoid the nearly impossible orientation situation that had occured in 1981, twelve targets (C1 to C12), nine of which were to be established, had to be coordinated by ground surveying methods near the time of photography. The same applied for the tiltmeter stations. Furthermore, eleven targets (three of them existing) were to be placed prominently for identification purposes. Size, shape and colour of the targets, as well as updated flight data were also given.

At the request of B.C. Coal's underground engineering department, certain changes in the aerial photogrammetry had to be made to cover the planned mining operations, and the flightlines were therefore extended across the Sparwood Valley near the B.C. Coal offices. An additional line was flown along that slope as well. The photography is kept on file for future reference for the planned mining area.

Limited time was available before the mine closure for surveyors to locate and re-survey the established points on the top of the ridge. Only the tilt stations were therefore resurveyed and newly coordinated before the closure of the mine. Suggested locations of air photo targets had to be modified according to the terrain conditions with thick bush and/or steep ground covered with loose gravel.

The reoccuring difficulties with ground control being either too sparse or else located in subsidence areas, has led to the development of a model displacement method. Here the movement vector is computed in an arbitrary system, e.g., the model coordinate system of one of the epochs, and subsequently an absolute orientation is performed. This means that the ground control needs to be coordinated for one epoch only.

According to (Moffit et al., 1980), the model coordinates of an epoch A can be calculated after the five parameters of relative orientation have been defined analytically with the aid of the coplanarity condition. They are

$$\begin{bmatrix} X_M \\ Y_M \\ Z_M \end{bmatrix}_A = \begin{bmatrix} X_{01} \\ Y_{01} \\ Z_{01} \end{bmatrix} + \lambda \begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix} + (0.5)d \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \qquad (1)$$

where

$[Z_M\ Y_M\ Z_M]_A^T$ = model coordinates of epoch A

$[X_{01}\ Y_{01}\ Z_{01}]^T$ = arbitrary coordinates of the left perspective centre

$[u_1\ v_1\ w_1]^T$ = refined photo-coordinates of the left photo

$[e_x\ e_y\ e_z]^T$ = vector components of the minimum distance between two conjugate rays

λ, d = scalar multipliers (functions of relative orientation parameters)

An absolute orientation of that model, if possible and desired, is achieved by a spatial similarity transformation.

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix}_G - SR_{(\omega,\phi,\kappa)} \begin{bmatrix} X_{MA} \\ Y_{MA} \\ Z_{MA} \end{bmatrix}_i - \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = 0 \qquad (2)$$

where

$[F_1\ F_2\ F_3]^T$ = functions of similarity transformation

$[X_P\ Y_P\ Z_P]_G$ = object coordinates of point P_i

$[X_{MA}\ Y_{MA}\ Z_{MA}]_i^T$ = model coordinates of point P_i in epoch A

$[X_T\ Y_T\ Z_T]^T$ = translation vector

$R_{(\omega,\phi,\kappa)}$ = rotation matrix

S = scale factor

Depending on the type of the available ground control points, either all the equations of (2), or the first two, or the last, can be used to determine the 7 unknown parameters. Equation (2) is of the form $F(\bar{X},L) = 0$ and has the following linearized form (Wells et al., 1971),

$$A\ X + B\ V + W = 0 \qquad (3)$$

in which

$$ {}_{m}A_{7} = \frac{\partial F_{j=1,3}}{\partial X_{i=1,7}} \quad , \quad {}_{7}X_{1} = [\delta S,\ \Delta\omega,\ \delta\phi,\ \delta\kappa,\ \delta X_{T},\ \delta Y_{T},\ \delta ZT]^{T} $$

$$ {}_{m}B_{n} = \frac{\partial F_{j=1,3}}{\partial L_{i=1,n}} \quad , \quad {}_{n}V_{1} = [v_{XM1}\ v_{YM1}\ v_{ZM1},\ \dots\ ,\ v_{ZMn}]^{T} $$

$$ {}_{m}W_{1} = [F_{1}^{o}\ F_{2}^{o}\ F_{3}^{o}\ \dots\ F_{m}^{T}] $$

m = $2H + V$, $n = 3(H + V)$

H = number of horizontal control points

V = number of vertical control points

The superscript (^{o}) indicates that W is the value of the function computed from initial approximate values of the 7 unknown parameters.

After the 7 parameters have been computed, the scale and the rotations are stored for further processing. Computation of the object coordinates from model coordinates of epoch A is optional.

Similarly, the model coordinates of epoch B are computed (equation (1)) again after the appropriate relative orientation parameters have been defined analytically.

Then, a spatial similarity transformation is applied to transfer model epoch B to the model coordinate system of model epoch A. Reference points, i.e., points which appear in both models but are not affected by movements, are used to determine the transformation parameters using equation (2). The seven unknown parameters are computed similarly to equation (3). The only difference lies in the formation of the design matrix B. Here B consists of two submatrices since the model points of epoch A are treated as observations and thus have their own covariance matrix. Therefore,

$$[2H + V]^{B}[6(H + V)] = [B_1 \quad B_2]$$

and

$$B_1 = \frac{\partial F}{\partial L_A}, \quad L_A = \text{observations corresponding to model epoch A}$$

$$B_2 = \frac{\partial F}{\partial L_B}, \quad L_B = \text{observations corresponding to model epoch B}$$

In addition, every reference point provides three observation equations because its x,y,z model coordinates are known.

At this stage, every point in the area of interest subjected to movement will have two sets of coordinates, since epoch A and B respectively are referred to the same coordinate system. Obviously, the differences between each pair of coordinates represent the model displacement vectors.

$$\begin{bmatrix} dX_M \\ dY_M \\ dZ_M \end{bmatrix}_i = \begin{bmatrix} X^1_{MB} \\ Y^1_{MB} \\ Z^1_{MB} \end{bmatrix}_i - \begin{bmatrix} X_{MA} \\ Y_{MA} \\ Z_{MA} \end{bmatrix}_i \tag{4}$$

where

$[dX_M \; dY_M \; dZ_M]^T_i$ = model displacement vectors of point P_i

$[X^1_{MB} \; Y^1_{MB} \; Z^1_{MB}]^T_i$ = coordinates of point P_i of model epoch B in the model epoch A coordinate system

$[X_{MA} \; Y_{MA} \; Z_{MA}]_i^{\,T}$ = coordinates of point P_i in model epoch A coordinate system

Now the actual components of the displacements along the three ground coordinate directions are obtained by applying the already stored 4 parameters (scale and rotations) to the model displacement vectors. Explicitly, the ground displacement vectors are given by:

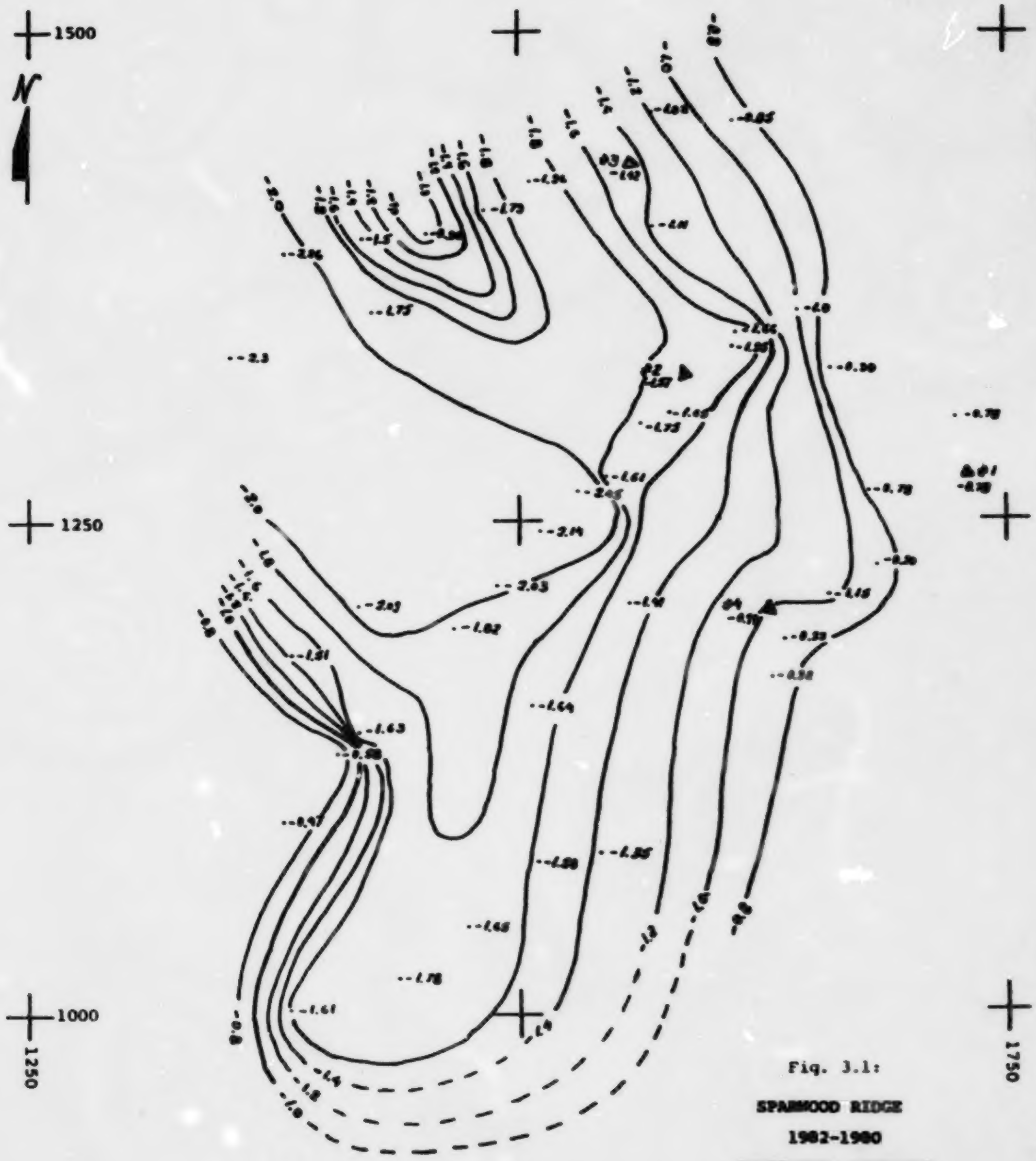
$$\begin{bmatrix} DX \\ DY \\ DZ \end{bmatrix}_i = SR_{(\omega,\phi,\kappa)} \begin{bmatrix} dX_M \\ dY_M \\ dZ_M \end{bmatrix}_i \qquad (5)$$

Now it was possible to use the epoch with the best available control for absolute orientation of the model displacements.

The results, given in Figures 3.1 and 3.2 show that subsidence continued in 1982, following predicted trends.

3.5 Discussion of the Results

The photogrammetric work at the study area proved, that with proper control for at least one epoch, subsidence accuracies of about 10 cm can be obtained using 1:7000 aerial photography. With the large horizontal component for the movements, the only feasible approach is the cross-identification method with subsequent numerical evaluation. The necessary software has been prepared, and excellent results have been achieved. Measurements on the precision comparator Zeiss PSK can be completed within one day of receiving diapositives of the area. This time includes the transfers on the Wild PUG as well. Analogue contouring of course provides for a better map, however has nothing to do with actual subsidence monitoring.



Fiq. 3.1:

SPARWOOD RIDGE

1982-1980

SUBSIDENCE CONTOURS

Scale 1:2500
Contour Interval 0.20 m

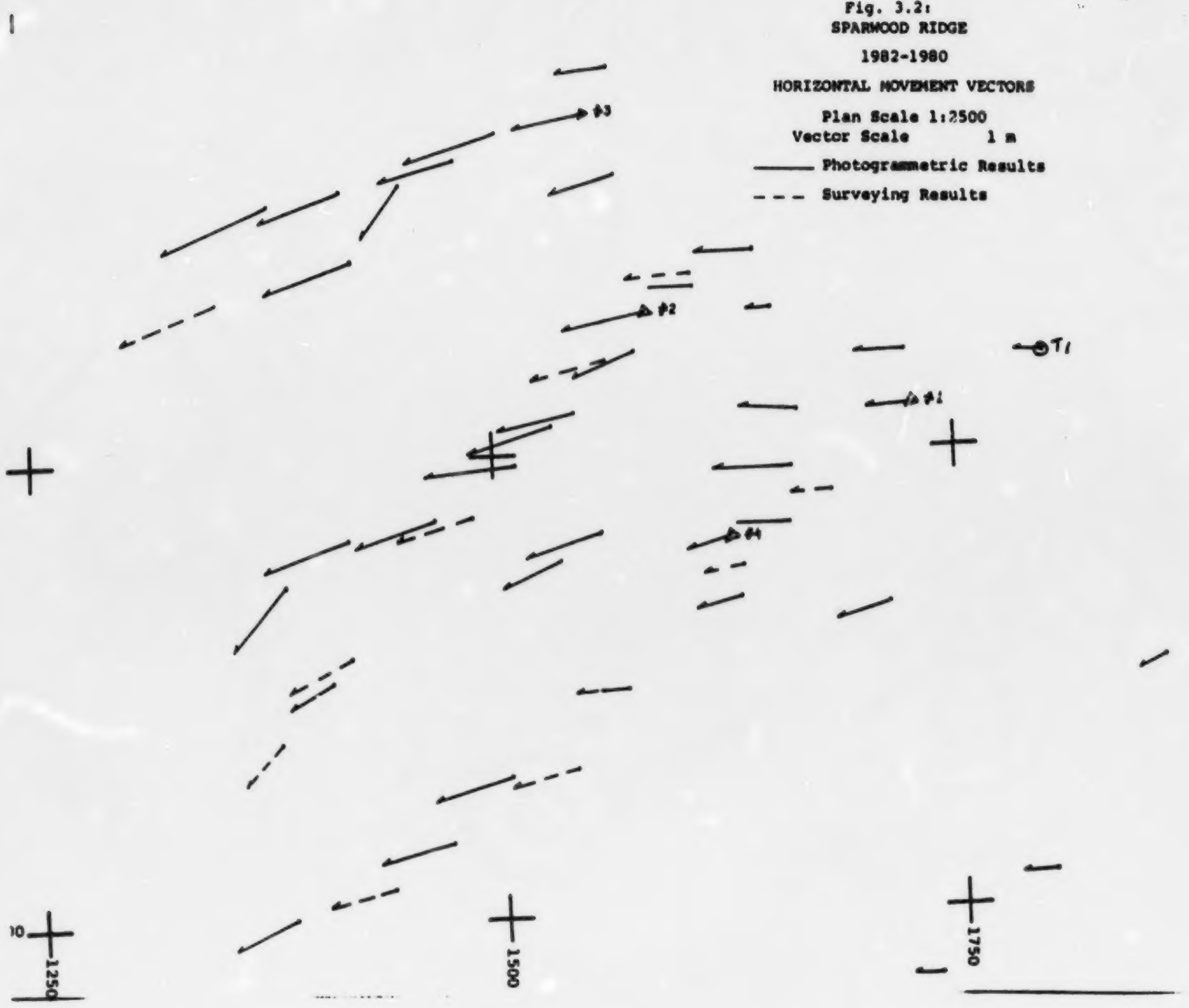


Fig. 3.2:
SPARWOOD RIDGE
1982-1980
HORIZONTAL MOVEMENT VECTORS
Plan Scale 1:2500
Vector Scale 1 m

4. EXPANSION OF TELEMETRY SYSTEM

The telemetry system's slave units are microprocessor-based data acquisition stations. The intelligence incorporated in the slave stations is the key to the reliable performance with highest data security under most adverse conditions. In addition, the one-year operating lifetime of battery powered slave stations in an unmanned environment was made possible by this approach. The philosophy underlying the design and implementation of the Slave and Master stations is exhaustively described in the 1980 Final Report.

With the advances in integrated circuit design and the availability of new analog and digital devices, it is possible to upgrade the existing slave design, thereby reducing its complexity and increasing its hardware reliability. This redesign is described and justified in this chapter. The new slave is identified by the addition of Vers 2 to its modules.

4.1 Objectives

An upgrade of the wireless radio-based data transmission link is to improve its reliability. The redesign of the slave's electronic circuitry by utilization of new integrated circuits is to simplify the circuitry, thereby reducing the chip count, increasing the hardware reliability and decreasing the battery power consumption. Previously experienced operation failures at extreme temperatures are to be reduced by the utilization of new analog components and quartz crystal components. The overall hardware reliability of the slave's electronics is to be improved by the use of commercially produced double-sided plated-through printed circuit boards of high manufacture standard and the simplification of module interconnections.

Field service and troubleshooting of the slaves is greatly facilitated by a newly designed slave test monitor with visual diagnostic aid and manual slave exercising capability. An improved packaging of the slaves' modules is to provide more user-friendly regular maintenance and more flexibility in the installation in the field.

The new slaves can be equipped with an alarm feature which allows initiation of data logging by the slaves themselves upon detection of abnormal conditions. This feature reduces the observation time uncertainty and can reduce the battery energy consumption.

Prime concern was given to full downward compatibility of the new slave Vers 2 stations with the older type slaves, Vers 1 and Vers 1.1. Any slave version can be used with any Master version as no operational functions are modified (except for the alarm feature which requires the new Master Vers 2).

4.2 Design Principles for New Slaves

The operation of the Vers 2 slave stations is identical to that of the Vers 1 and Vers 1.1 slaves. The 1980 Final Report elaborates on the operational principles and the underlying ideas. In this report, only the new design and its implication is addressed.

The VHF-radio link of the Vers 1 telemetry system was shown to be the most problem prone part of the system. The Vers 2 slave units are equipped with the new REPCO VHF transmitter/receivers as used in the upgraded Vers 1.1 slaves. The basic circuit changes are described in Section 2.2 of this report. The block diagram of the affected Telemetry

Module TLM is illustrated in Figure 4.1 (replaces Figure 4.10 of 1980 Final Report). The pre-detection filter (bandpass 1070/1270 Hz) extracts the relevant FSK signals from a noise-contaminated receiver signal. This filter is responsible for a greater noise insensitivity of the VHF radio link, contributing to a more reliable wireless radio communication between Master and Slaves, particularly under adverse conditions (VHF disturbance, rain and snow, obstacles in the direct viewing line Master-Slave).

The REPCO VHF radio link components do not appear to provide the excellent audio frequency transfer characteristics as did the Motorola HT210 devices installed in Vers 1 Slaves. This shortcoming, however, is overcome by the use of the pre-detection filter. As the REPCO devices do not produce any of the RF-related problems that were experienced so severely with the Motorola units (Vers 1), they are considered superior RF-radio link devices. No significant sensitivity to antenna matching, location, and RF-injection into data and power cables was detected.

Two improvements are added to reduce the chip count of the Slave's electronic circuitry, affecting the microprocessor control unit MPCU and the data acquisition module DAQM.

The analog-to-digital converter of the DAQM transferred its data to the MPCU via the input port (MPCU, IC3) in Vers 1. The converters employed are compatible with the micro processor's bus system and are now interfaced directly with the bus, thus omitting the port IC3 (MPCU, Vers 1). The block diagram of the DAQM (Figure 4.9 in 1980 Final Report) is not affected.

The Slave's control software is held in three read-only memories in Vers 1 (MPCU, ICG, 7, 8). New memories of larger size and military specifications are now available. Thus, the three chips are replaced by a

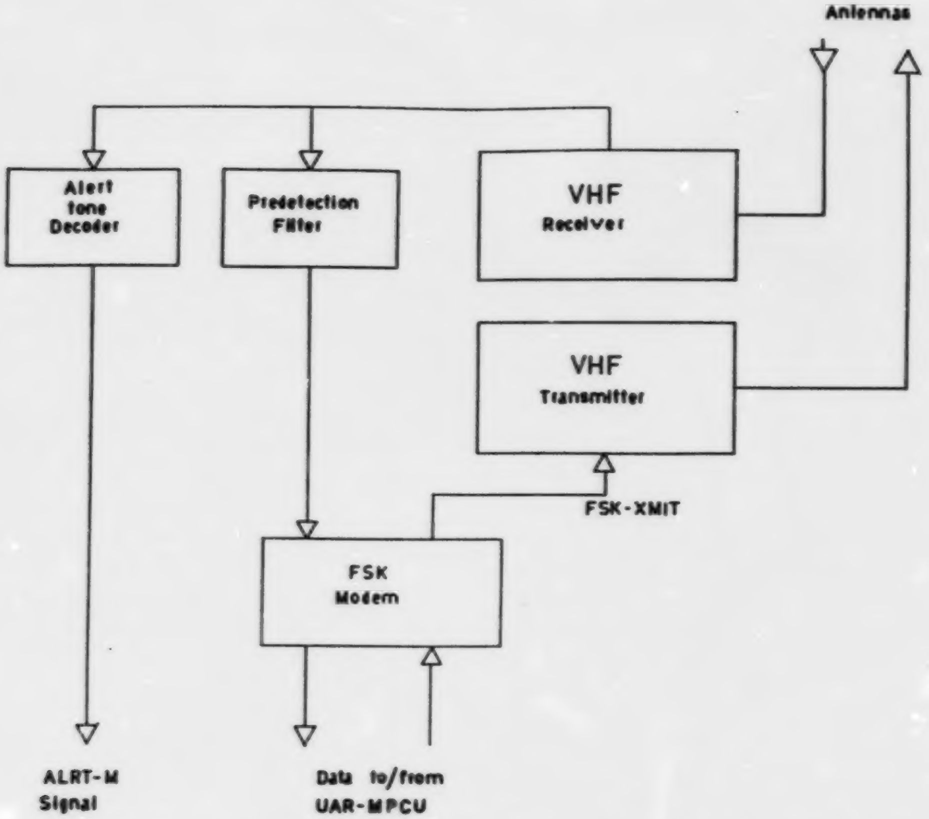


Fig. 4.1: Block diagram of Telemetry Module TLM (Slave Vers 2).

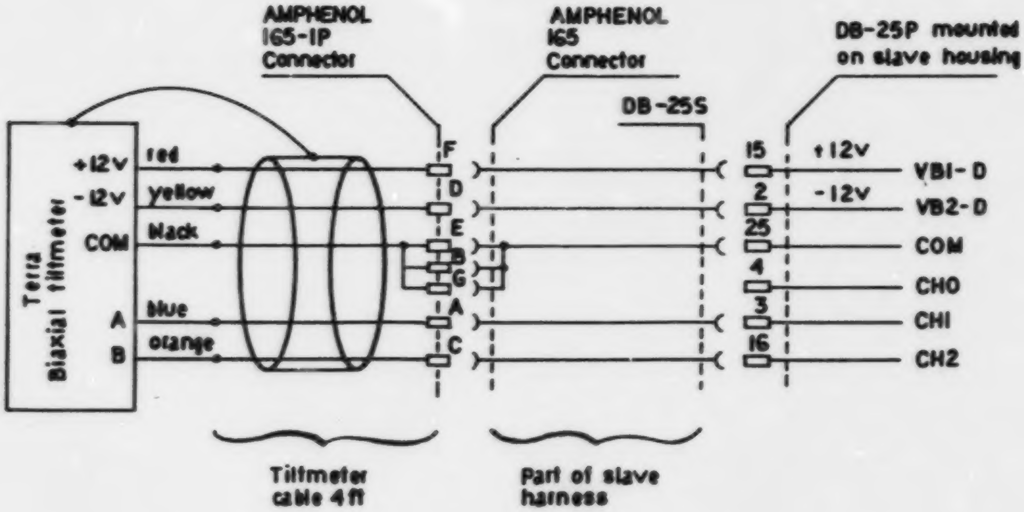


Fig. 4.5: Tiltmeter Connection Scheme (Slave Vers 2).

single component. This single component now also contains the software support of the mini-terminal used for program development, debugging and maintenance. The block diagram of the new MPCU module is shown in Figure 4.2 (replacing Figure 4.8 of 1980 Final Report).

The home address of each Slave station is independent of the particular Slave's control software. In Vers 2 Slaves, the address is variable and user selectable by jumper. Upon power-up of the MPCU's micro-processor, the address is read into the processor's memory via a gating device. This variable address selection scheme makes possible the ready exchange of slaves and part of the slave's electronic module without a compulsory change of the home address.

The above three integrated circuit modifications result in the desired reduction in chip count, fewer interconnections and reduced battery power consumption. An overall increase in hardware reliability can be expected.

The timing of the Vers 2 MPCU is changed to permit the use of quartz-crystals of higher frequency which are less susceptible to oscillation failures at extreme temperatures. In addition, new operational amplifiers are being used for the TLM module which are less prone to unwanted oscillations due to parasitic feedback at extreme temperatures.

The power distribution module PDU is affected by two modifications. The relay powering the DAQM in Vers 1 is removed and the latter module is directly powered by the MPCU. In place of the former relay, a transmitter/receiver power switching relay (rel 31) is added in the Vers 2 PDU. These changes are summarized in the block diagram in Figure 4.3.

The above mentioned simultaneous power-up of the MPCU and DAQM gave rise to a beneficial change of the time-out condition of the Vers 2

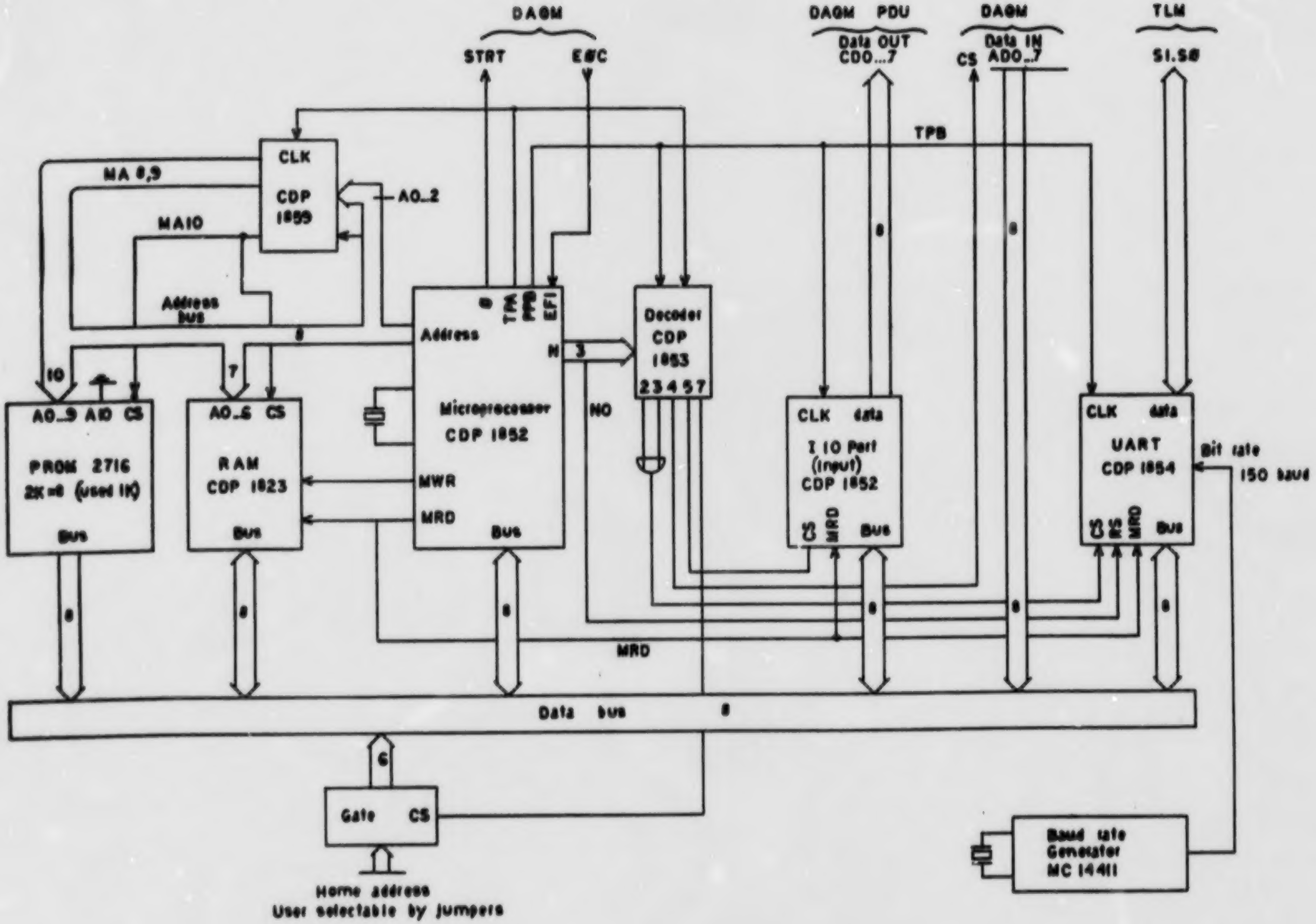


Fig. 4.2: Block diagram of Microprocessor Control Unit MPCU (Slave Vers. 2).

Slave. Each Slave station which does not recognize its home address during an interrogation poll, returns to the stand-by mode immediately. This action reduces the power-up period of non-addressed Slaves during interrogations. In addition, the wait-time between a successful Slave addressing event and the beginning of the data logging process (to allow for settling of the sensor output signals after turn-on) can be reduced without affecting the settling time itself (≤ 7 sec). Together, these changes reduce the overall power-up period of Slave stations and lead to a lower battery energy consumption (12/2 sec for Vers 2 as compared to 17/7 sec for Vers 1 Slaves for addressed/non-addressed slaves). As an added benefit, the Vers 2 Slave stations react faster to calls from the Master station and noticeably speed up the data acquisition process. The modifications are illustrated in the state diagram of Figure 4.4 (replaces Figure 4.3 of 1980 Final Report).

In the Vers 1 Slave stations, the external sensors (tiltmeters) are connected to the analog input channels Ch 1 and Ch 2 via pre-amplifiers. These analog amplifiers introduce temperature and battery-voltage dependencies which need to be compensated for. The Vers 2 Slaves utilize tiltmeters which are selected for an output signal range (-5V...+5V) corresponding to the desired inclination range to be measured. Consequently, no pre-amplifiers are needed and the calculation of the measured tilts becomes entirely independent of the Slaves' components. The tiltmeter connection to the Slave is made via a set of sealed connectors as shown in Figure 4.5. This approach provides easier field installation and maintenance of the combined tiltmeter-Slave units.

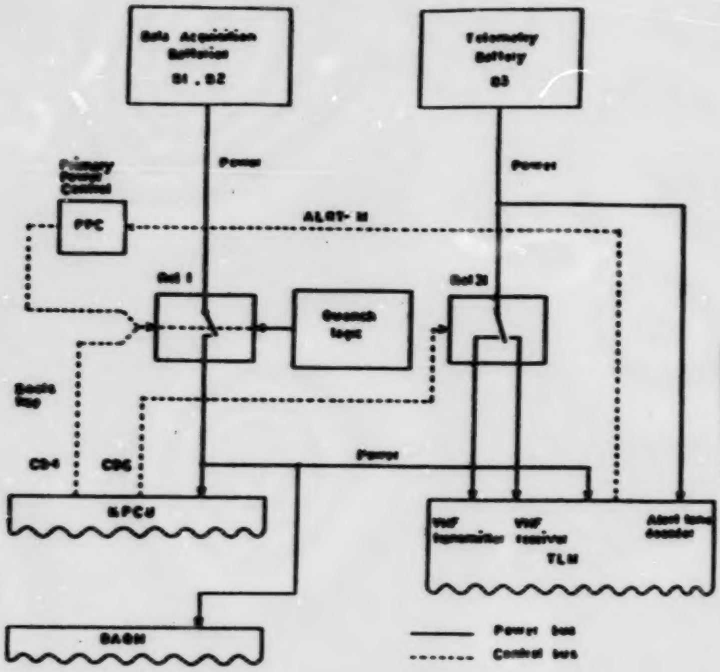


Fig. 4.3: Block diagram of Power Distribution Unit PDU (Slave Vers 2).

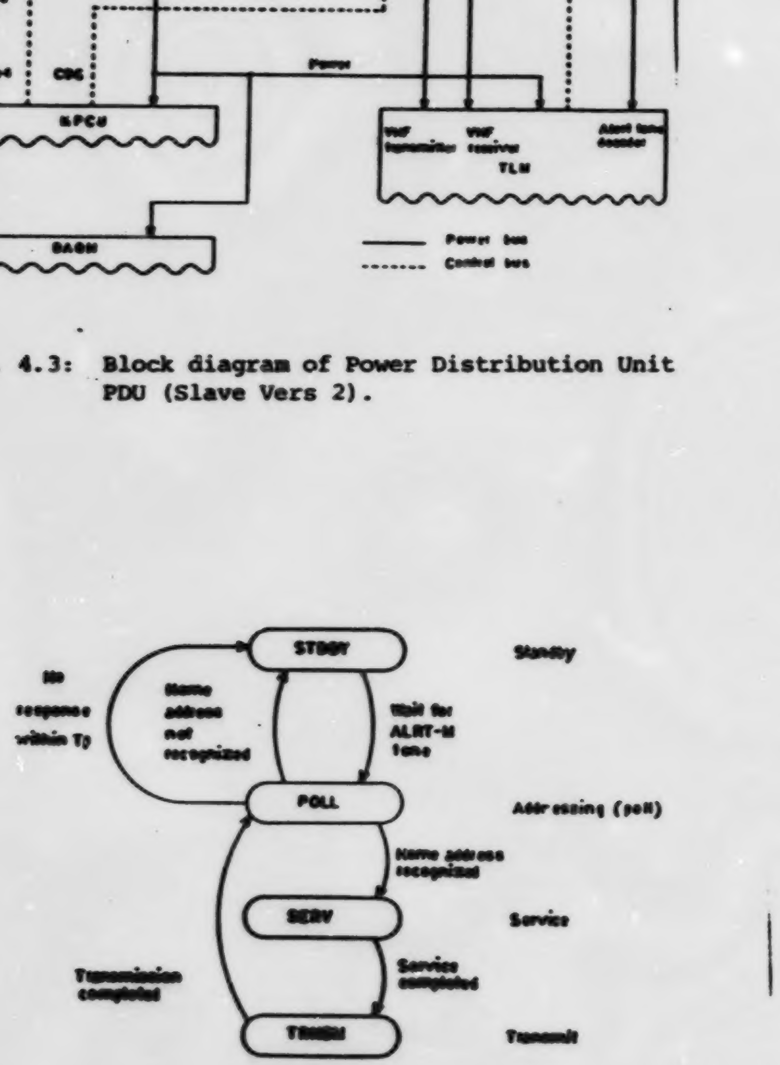


Fig. 4.4: State Diagram of Slave's Operational Procedures (Vers 2).

4.3 Circuit Description of New Slaves

The electronic circuitry of the Vers 2 Slave stations are described in this section. An exhaustive description of the basic design philosophy is provided in the 1980 Final Report, Section 4.3. Here, only those circuits which differ from the Vers 1 Slave design are presented.

4.4 Slave Test Monitor

The Slave Test Monitor Vers 2 has been designed to facilitate the regular maintenance, diagnostic and troubleshooting of all eletronic parts of the Slave stations. Its operation and indicator layout is devised to permit successful use by less trained persons as well as providing detailed information to technically oriented users familiar with the Slave electronics. The Test Monitor can be used in a passive monitor mode to examine the flow of events taking place in the Slave upon interrogation by the Master, or in an active mode where the Slave's functions can be exercised manually.

The Test Monitor is not dedicated to only one Slave, but can be connected to any Slave without disturbing the operation of the latter. After the testing session, the Test Monitor is removed for use with other Slaves. The monitor interacts visually with the user by means of illuminating indicators which show the flow of activities in the Slave. Apart from the visual indication, a selected set of critical analog and digital signals internal to the Slave's electronic circuitry is accessible on jacks for further testing and diagnosis. These signals include battery voltages, asynchronous transmission signals for timing purposes, squelch signal for receiver adjustment, and sensor signals (tiltmeter output) for manual tilt measurement. An earphone jack is available through which the clarity of the received FSK signal can be tested.

The front panel of the Slave Test Monitor is shown in Figure 4.13 and the photograph in Figure 4.14. Starting from left, the occurence of successive activities is reflected by the illuminating signal lights. A typical interrogation cycle initiated by a Master call would activate the following lights:

only VB3-R on:	Slave is in stand-by mode
SQUELCH:	Master transmitter on
ALRT-M:	Master alerts all Slaves
VB1-D, VB2-D:	Slave powers up
SDI:	Slave receivers poll from Master
DAQM ON:	Data acquisition active
ADC:	Data from sensors is logged
VB3-R off:	Slave transmitter turns on
VB3-X on	
SDO:	Slave transmits data to Master
only VB3-R on:	Slave returns to stand-by mode.

The sequence of illuminating lights follows exactly the cycle of starts in the Slave. Clearly, any malfunction in this sequence is readily detectable.

Three push-bottons serve in the active mode to exercise manual control. The Start button initiates a start-up cycle without data logging which can be interrupted by pressing the Time-out button. The Slave's transmitter can be turned on for testing purposes by pressing Transmitter On.

The Slave Test Monitor can only be used with the Vers 2 Slaves. The circuit diagram of the Slave Test Monitor is shown in Figure 4.15.

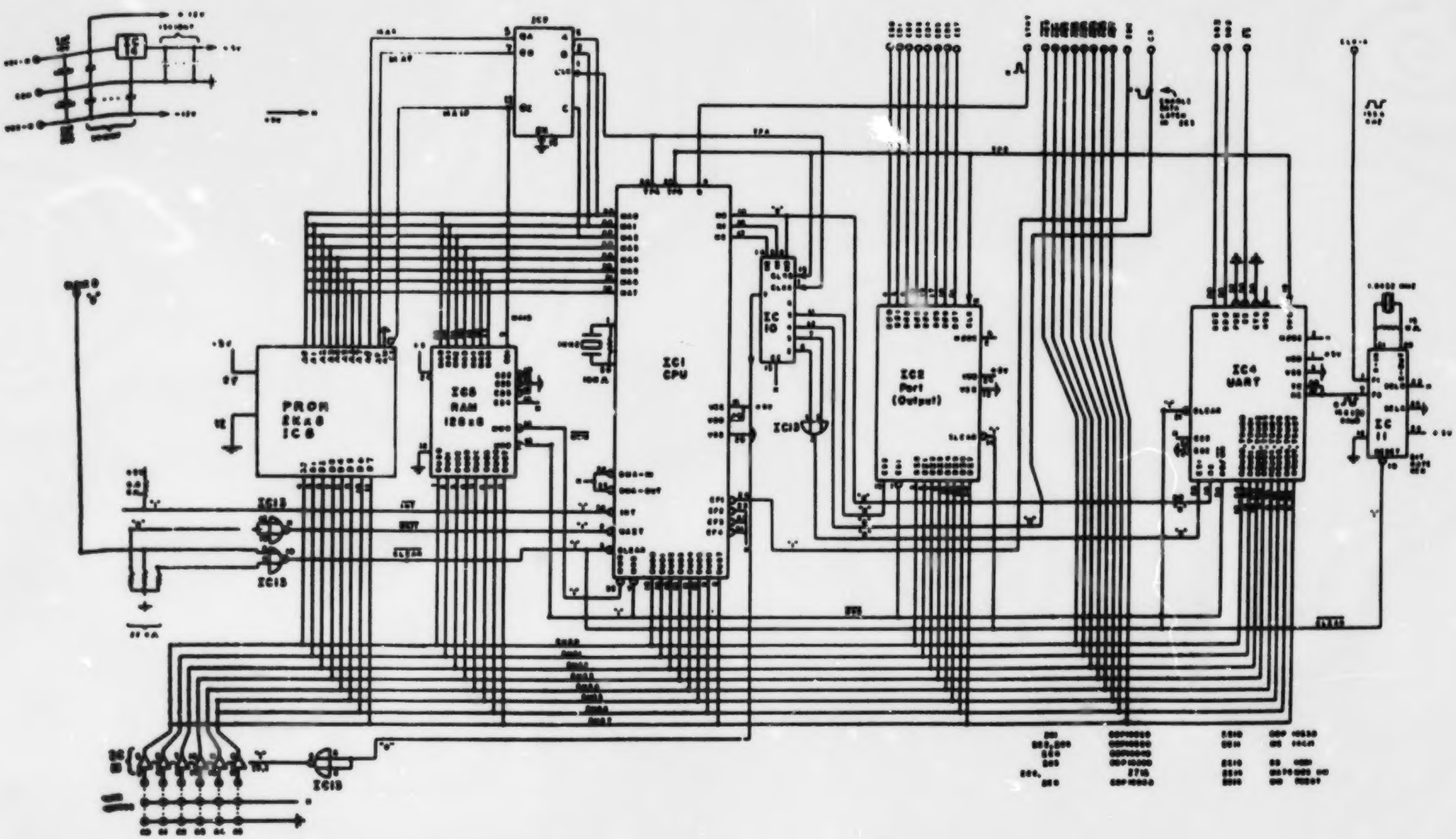


Fig. 4.6: Microprocessor Control Unit (Slave Vers 2).

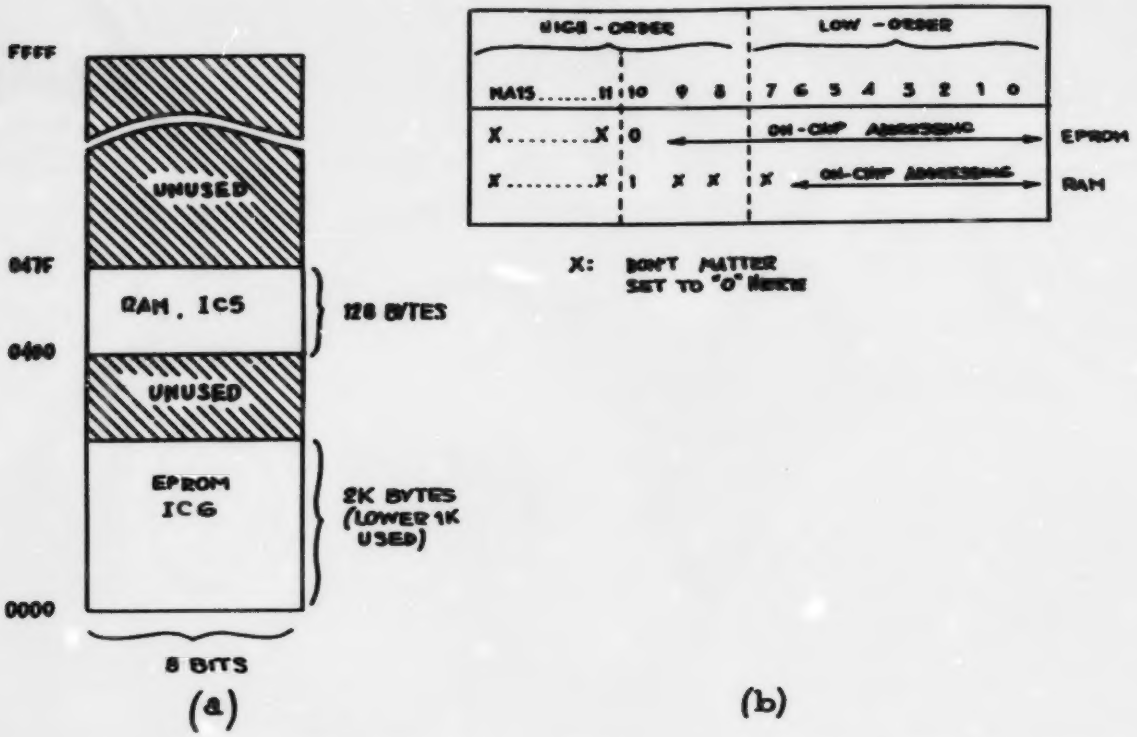


Fig. 4.7: Memory Address Space and Address Bus Decoding, MPCU (Slave Vers 2).

	Peripheral	N-Code	Function
IC21	ADC data	4	read $\overline{AD0}$ ... $\overline{AD7}$
IC2	control data	5	write CD0 ... CD7
UART	Transmit Data	2	write
	Receive Data	2	read
IC4	Control	3	write
	Status	3	read
Key-pad IC104	Input port	6	read upon interrupt
Display IC105	Output port	6	write
IC15	Slave address	7	read

Fig. 4.8: Addressing Scheme of Peripheral Interfaces Using N-code Selection, MPCU (Slave Vers 2).

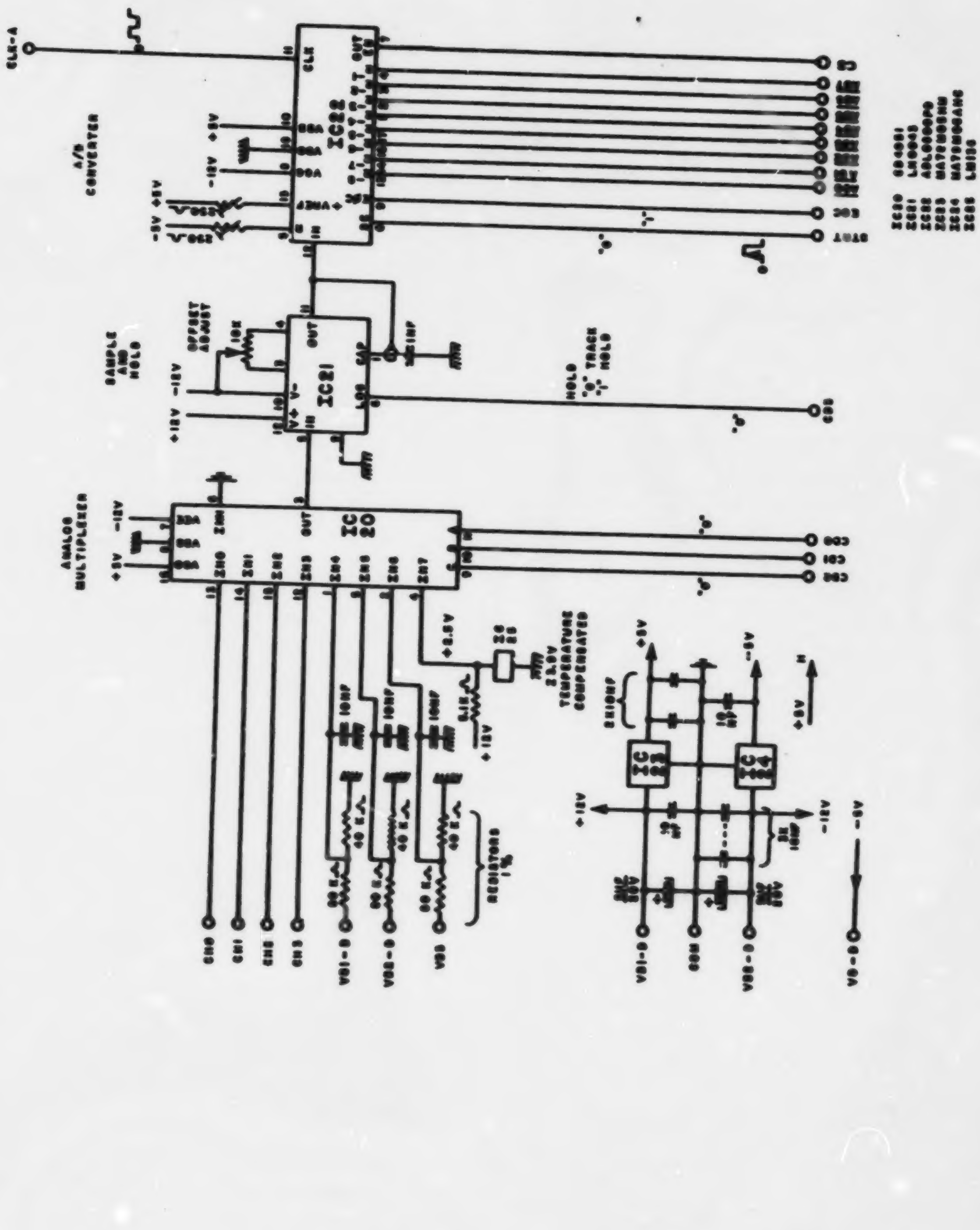


Fig. 4.9: Data Acquisition Module DAQM (Slave Vers 2).

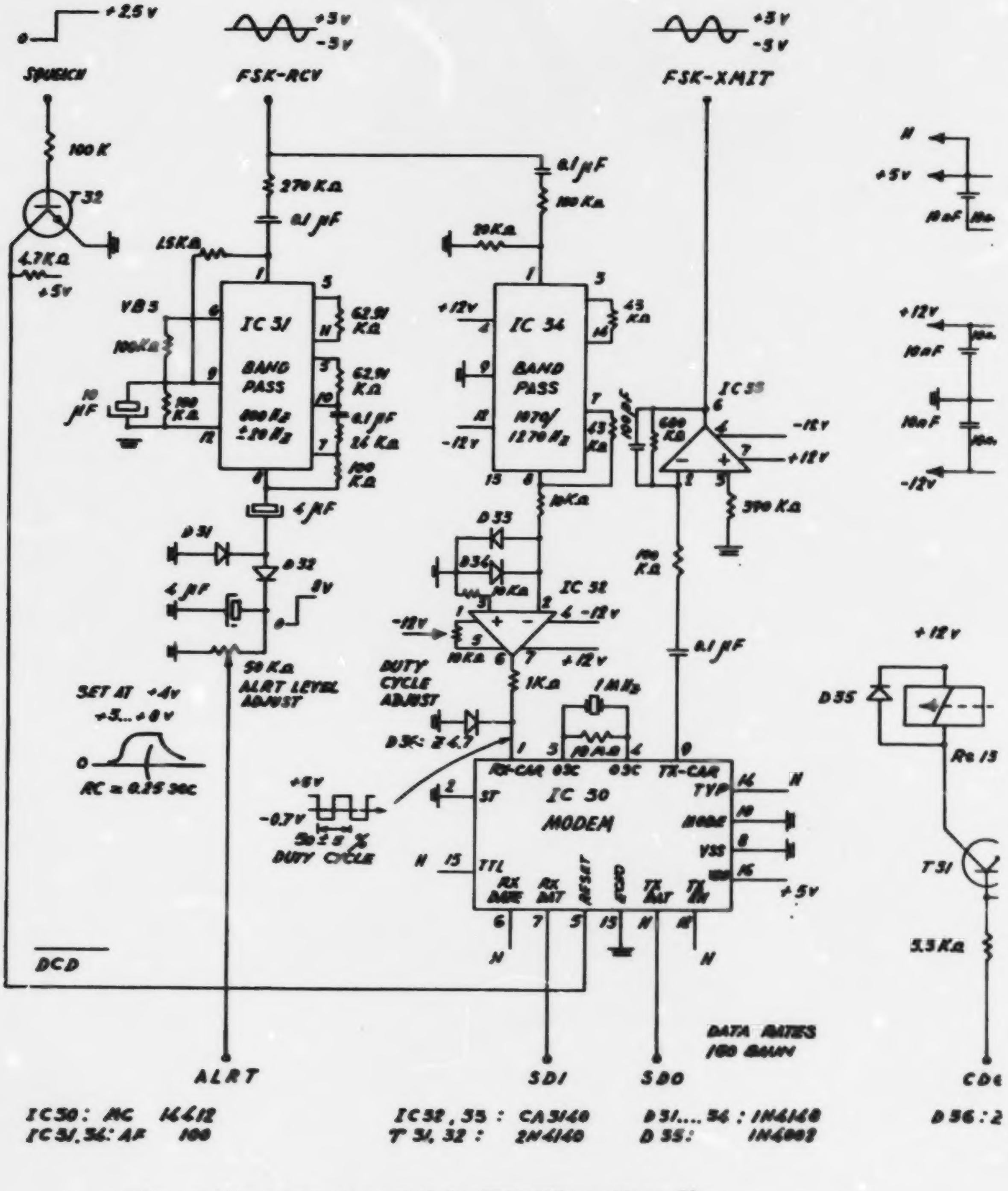


Fig. 4.10: Telemetry Module TLM (Slave Vers 2).

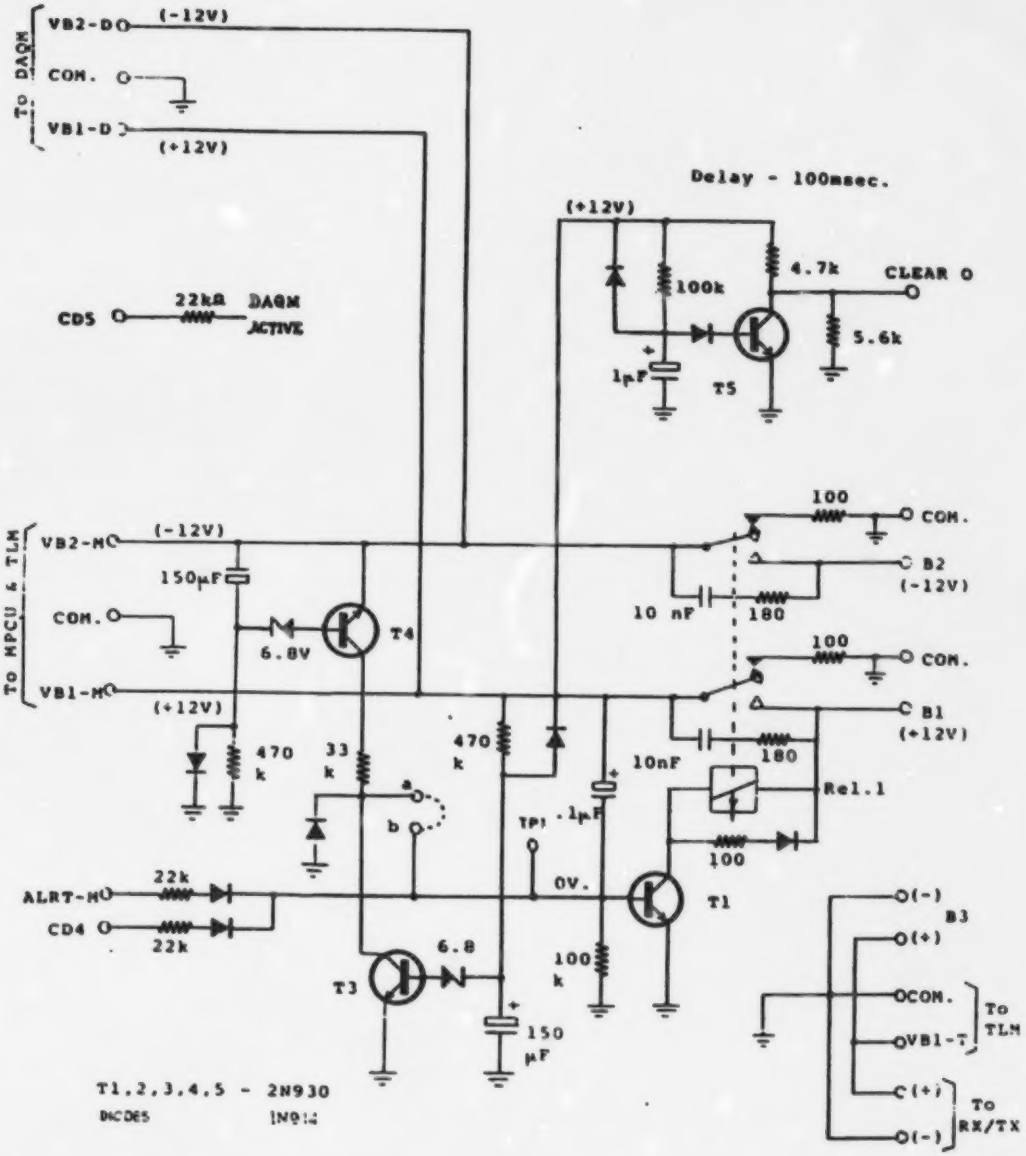


Fig. 4.11: Power Distribution Unit PDU (Slave Vers 2).

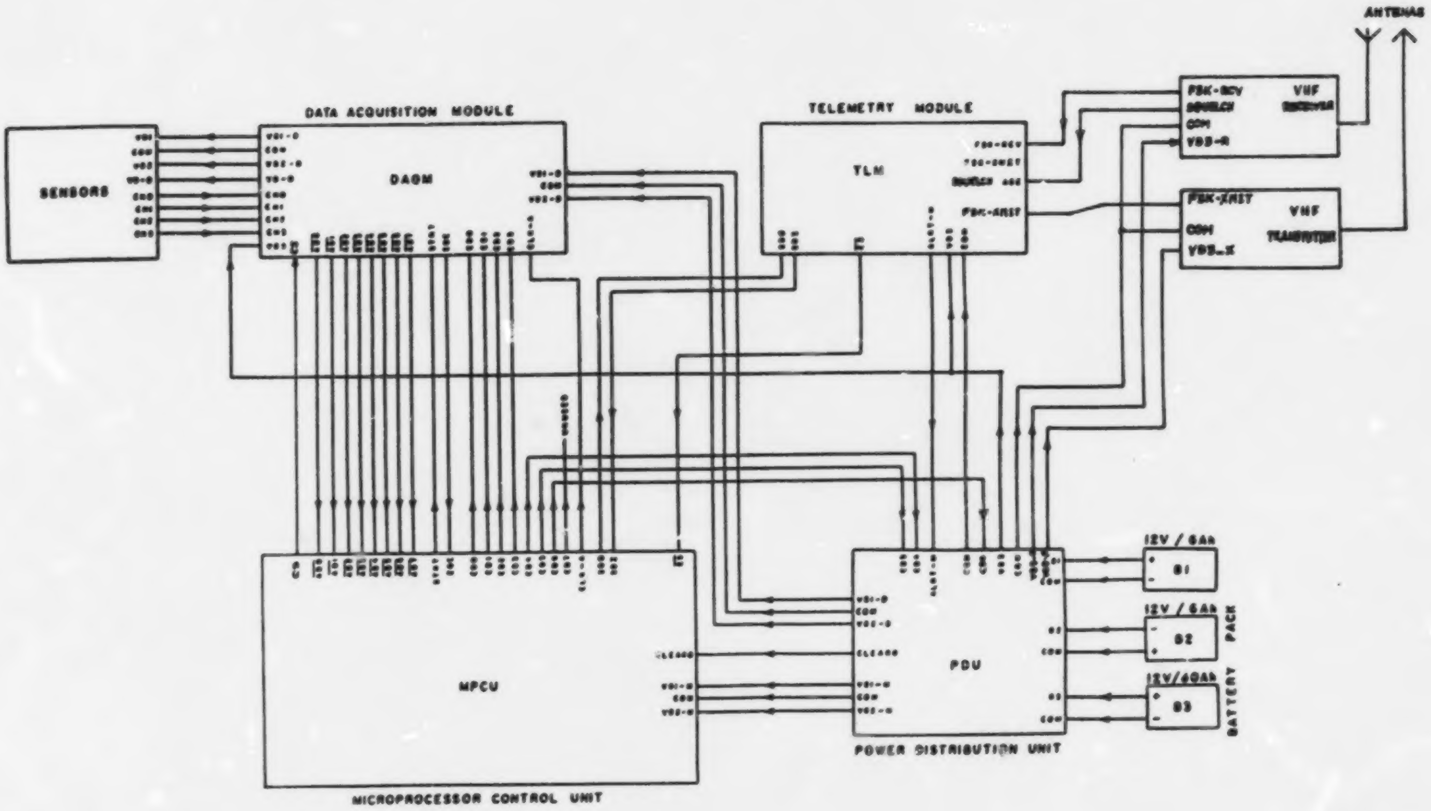


Fig. 4.12: Module Interconnection Scheme (Slave Vers 2).

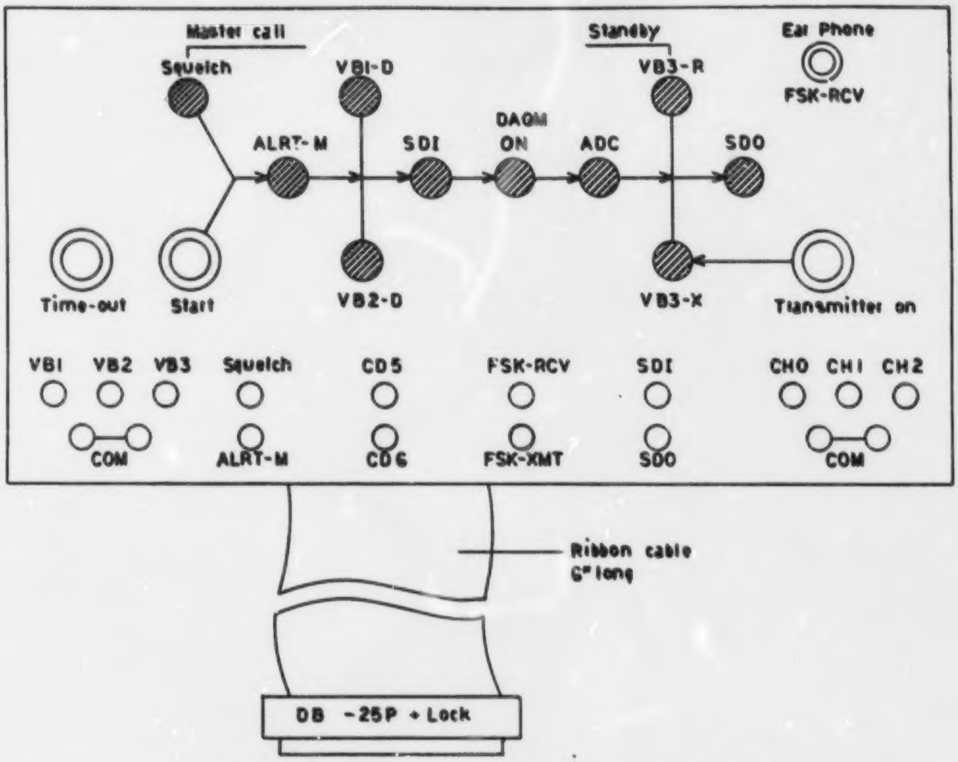


Fig. 4.13: Front Panel Layout of Slave Test Monitor (Vers 2).

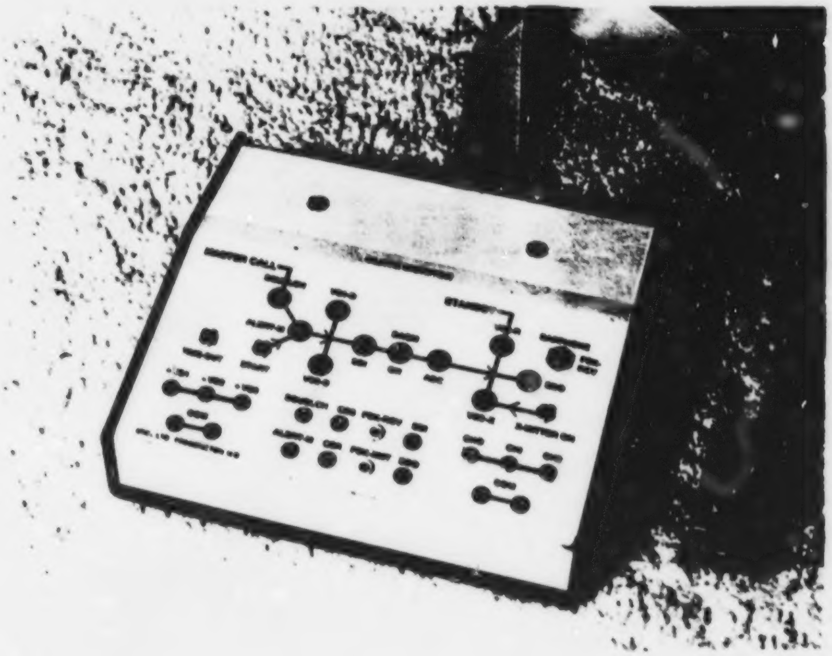


Fig. 4.14: Slave Test Monitor (Vers 2).

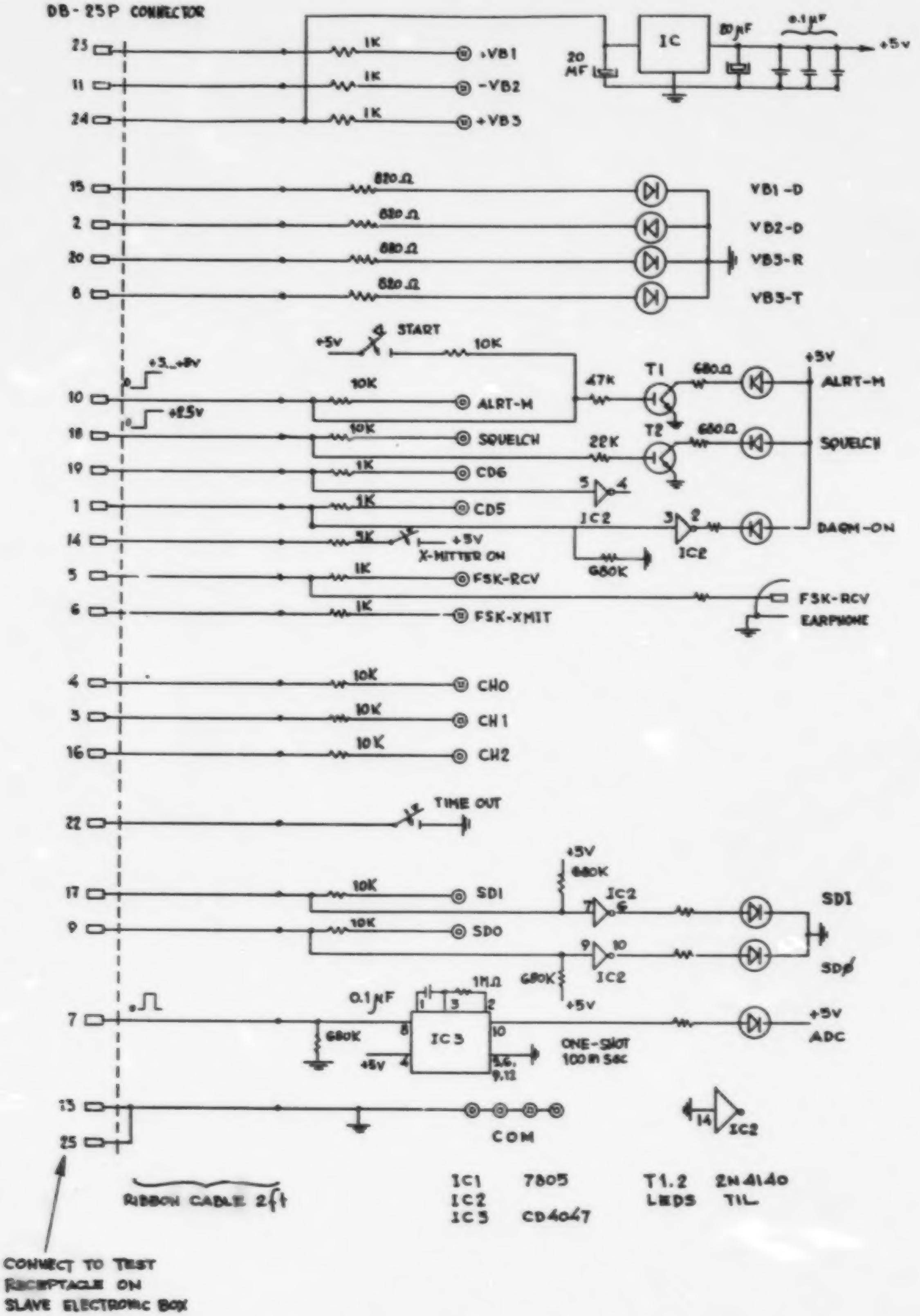


Fig. 4.15: Slave Test Monitor, Circuit Diagram (Vers 2).

4.5 Choice and Calibration of New Tiltmeters

The successful three years' experience with the Terra Technology bi-axial tiltmeters, their reliability and reasonable price, led to the decision to use the same type of tiltmeters (servo- accellerometer type) in the expanded telemetry system. The basic principle and characteristics of the tiltmeters were described in the 1980 Final Report. Three new tiltmeters were purchased and tested. The only difference between the old and the three new tiltmeters is the maximum tilt range of $\pm 6^{\circ}$ and $\pm 1^{\circ}$ respectively, corresponding to the maximum voltage range of ± 5V.

Thus the new tiltmeters do not require the amplification of the output signal unless a smaller than $\pm 1^{\circ}$ range would be required. It makes the calibration of the system and calculation of the tilts simpler than in the old system. The tilt α in seconds of arc is calculated from:

$$\alpha'' = \frac{r}{K}(1+\epsilon) + \frac{\tau}{K}\,T + \frac{\Delta}{K}\,t = \frac{r(1+\epsilon) + \tau T + \Delta t}{K}$$

where r: output signal in [mV]

K: conversion factor (from mV to seconds of arc) in [mV/"]

ϵ: coefficient dependent on the drop in the power supply voltages. This coefficient is taken as equal 0 if the drop in the voltages does not exceed -10% of the initial voltages.

T: temperature in [°C] at the field station (measured with a separate sensor)

τ: temperature compensation coefficient in [mV/°C]

Δ: drift correction in [mV/day]

t: time lapse in days between the initial (reference) tilt reading and the actual reading.

The determination of the conversion and the compensation coefficients K, τ and Δ was made at the University of New Brunswick where laboratory facilities, including stable pillars, were made available for this project. The three new tiltmeters were calibrated together with the repaired old tiltmeter No. 105 (field station #0).

4.5.1 Determination of the conversion factor K.

The same arrangement for the tilt calibration has been used as described in the 1980 Final Report of the previous contract, using the tiltable plate coupled with a Wild T-2 theodolite. The calibration was performed at a constant temperature of +23°C changing the tilt of the testing plate in steps of 10 minutes of arc over the range of ±1°. Each sensor (sensors A and B) of the bi-axial tiltmeters was calibrated separately. The conversion factors K have been determined through linear least squares fitting using observation equations of the form:

$$y_i + v_i = b + K\alpha_i$$

where α_i: angle of tilt

y_i: observed change in [mV] of the readout

v_i: residual of the observation

The results are summarized in table 4.1, where σ_K are standard deviations of the estimated conversion factors K.

Table 4.1 Estimated Conversion Factors and their Standard Deviations.

Tiltmeter No.		A-axis	B-axis
105	$K=$	0.2302	0.2304
	$\sigma_K=$	0.00008	0.00004
107	$K=$	1.3784	1.3858
	$\sigma_K=$	0.00042	0.00072
108	$K=$	1.3824	1.3776
	$\sigma_K=$	0.00044	0.00070
109	$K=$	1.3813	1.3800
	$\sigma_K=$	0.00044	0.00072

The maximum standard deviation $\sigma_K = 0.00072$ corresponds to $\sigma_\alpha = 1.4''$ for $\alpha = 1^\circ = 3600''$ which is much smaller than the allowable standard deviation of $30''$ in the tilt determination in subsidence monitoring.

The least squares adjustments gave a maximum residual $v_{max} = -10.9$ mV (B-axis of Tiltmeter No. 107) which corresponds to $8''$ in angular units. Note that the replaced tiltmeter No. 105 has a conversion factor that is about 6 times smaller than for other tiltmeters because its range is $\pm 6^\circ$ vs $\pm 1^\circ$ for the new tiltmeters.

4.5.2 Determination of the compensation coefficient ε

The coefficients ε are accepted as being the same as given in the 1980 Final Report. For all practical purposes, one can take $\varepsilon = 0$ as long as the voltages V-1 and V-2 of the power supply to two tilt sensors of the bi-axial tiltmeters do not drop more than -10% of the initial voltage. For larger differences ΔV-1 and ΔV-2 the coefficient ε is interpolated (two-dimensional interpolation) from Table 4.2 (copied from the 1980 Final Report).

Table 4.2 Discrete Values of the ε Coefficient

ΔV-1 ΔV-2	-25%	-15%	±0%
-25%	0.033	0.019	0.029
-15%	0.036	0.004	0.002
±0%	0.038	0.007	±0

4.5.3 Drift evaluation

Several long term drift tests have been performed on the three new and the replaced #105 tiltmeters. The drift phenomena affect all types of tiltmeters and are not well understood. The longest test lasted 57 days. Details of the test and a graphical display of the results were given in the April 1983 Monthly Report. The general conclusion is, that all the tested tiltmeters do not indicate any systematic drift after a settling time, ranging from 2 to 45 days in the worst case (Axis B of #109), depending on the tiltmeter. Thus the tiltmeters for long term monitoring should be installed up to two months prior to commencement of the monitoring process.

Due to the postponement of the installation of the telemetry system until August 1984 it is recommended that an additional drift test over a 60 day period should be made just before the installation.

4.5.4 Temperature compensation

All four tiltmeters have been tested at four different temperatures: +23°C, +10°C, -3°C and -15°C using the natural environmental conditions of the winter season and the room temperature of the laboratory of the University of New Brunswick. The vertical orientation of the tiltmeters was controlled by means of the reference testing plate (see Fig. 2.7 in Section 2.4) equipped with high resolution (better than 5 seconds of arc) spirit levels. All eight sensors of the four bi-axial tiltmeters have shown a linear relationship between the voltage output and temperature. Graphs of the outputs at four different temperatures were given in the April 1983 Monthly Report and are not repeated in this report. Straight lines have been fitted to the four temperature points. A summary of the results in form of conversion parameters τ (reduction of the voltage output to 0°C conditions) is provided in Table 4.3.

Table 4.3 Conversion Factors τ in [mV/°C]

Tiltmeter No.	A-axis	B-axis
105	0.0	1.2
107	0.0	5.0
108	3.2	13.7
109	-8.9	-10.0

The corrected (reduced to $0^{\circ}C$) voltage output is calculated from:

$V_o = V + \tau T$

where V: actual voltage readout in [mV]

T: tiltmeter temperature.

The linear fitting gave maximum residuals of 20" (A-axis of No. 107 and A-axis of No. 105) which is within the tolerances of ±60" at 95% probability as required by the project.

4.6 Construction of the New Slave Units

Each of the Slave units consists of two waterproof steel boxes, interconnected by a short cable as shown in the photographs of Figure 4.16. Box "A", contains the electronic components Figure 4.17:

1) A moisture proof steel case containing the Microprocessor Control Unit (MPCU)
2) Repco VHF transmitter
3) Repco VHF receiver
4) Helical antenna mounted on top of a 1.5 m steel tube

Box "B", houses the batteries Figure 4.18:

1) One set of two 12V, 6Ah, Gel-cells for the MPCU, VB1 and VB2
2) One, 12V, 55 Ah, Gel-cell for the Receiver/Transmitter, VB3

The Slave units had to fulfill the following environmental and electrical criteria:

1) Reliable operation between $-25^{\circ}C$ and $+40^{\circ}C$
2) Isolation from external influences of moisture, dust, and animal interference
3) Unattended operation during the winter period

Box "A" housed the electronics, the radio frequency link, and was the focus of most work.

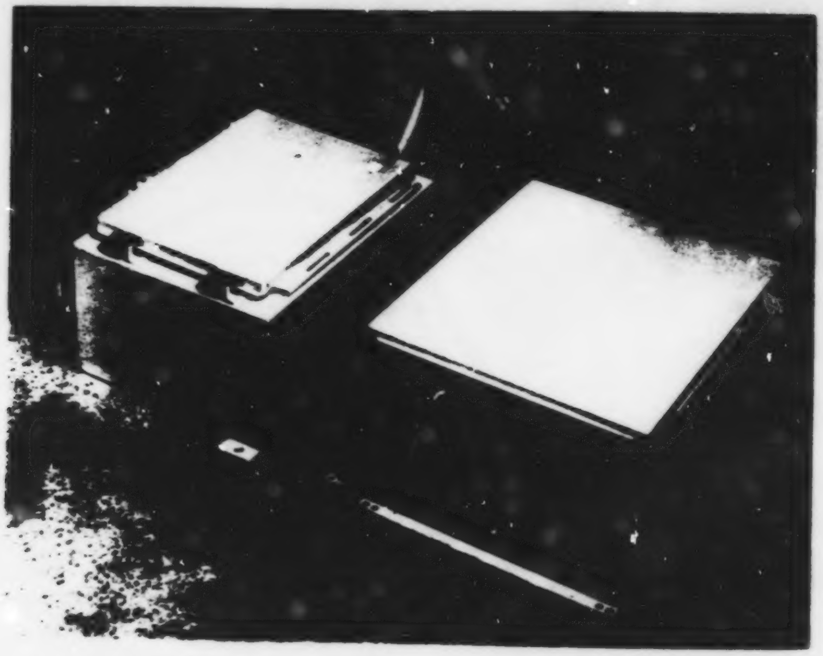


Fig. 4.16: Modularized Construction of a Slave Station (Vers 2)

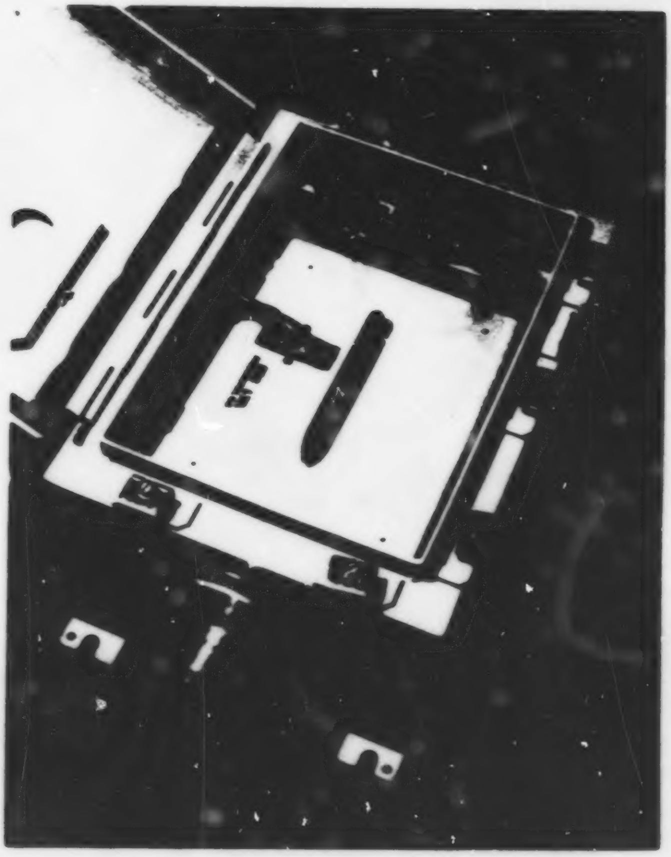


Fig. 4.17: Component Arrangement in a Slave Station (Box A, Vers 2)

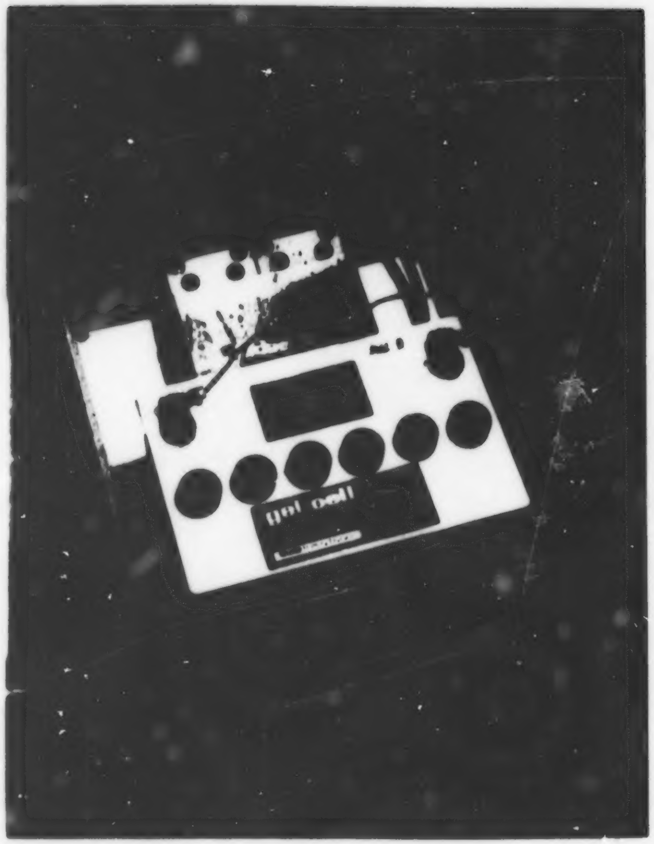


Fig. 4.18: Battery Arrangement in Box B
(Slave Vers 2)

Fig. 4.19: Dual Antenna Arrangement
(Slave Vers 2)

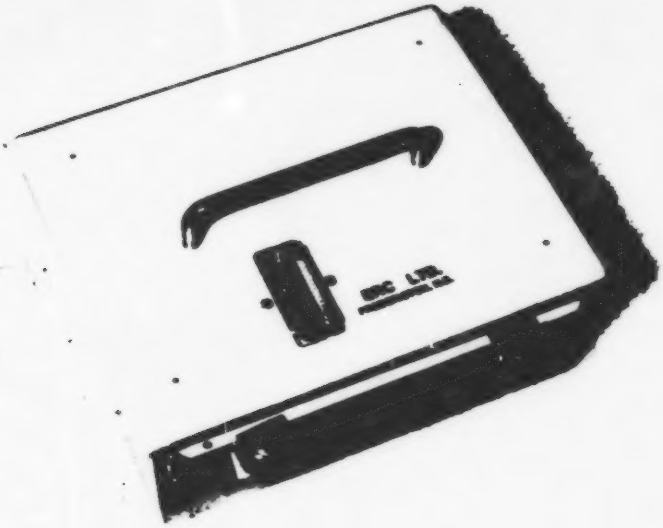


Fig. 4.20: Electronics Assembly Housing (Slave Vers 2)

Fig. 4.21: Printed Circuit Board Layout for Electronics Assembly (Slave Vers 2)

Fulfilling the first requirement, all electronic components, batteries as well as the receiver/transmitter set were carefully chosen to have specifications permitting operation within this range (Fig. 4.22).

From our past experience with working Slave stations which utilized the Motorola HT210B transceivers, it was clear, that the transmitter/receiver link represented the most critical component of the system. The above experience resulted in the selection of a transceiver link that would fulfill the low temperature requirement and allow good electrical shielding between the microcomputer and the link. The Motorola HT220 walkie-talkies were replaced with Repco Series 810-055 Receiver, and Repco 810-040 Transmitter.

Each Repco unit came from the manufacturer as a single 8.4 cm^2 circuit board, which was mounted in a separate aluminum die cast box. Signal and power connections were brought out through low pass feedthroughs to the side of the box, where a small shielding enclosure held a 9 pin "D" type connector. The antenna input/output was accessed through a separate UHF Type receptacle. Unlike with the Motorola units, it was decided not to use an antenna relay as a measure to improve raliability, and reduce antenna impedance mismatch. Separate receive/transmit helical "rubber duckies" were mounted on machined adaptors at the end of a 1.5 m high steel tub as shown in the photograph of Figure 4.19 and in Figure 4.23), and separate coaxial leads run to the UHF connectors on the transmitter and receiver boxes (Fig. 4.24). In this manner any of the link components is easily removed and replaced.

The same follows for the Microprocessor Control Unit, which was mounted in a Hammond 195-14141 moisture and dust tight steel box, with an Amphenol "D" type 25 pin connector coupling the unit to a wire harness

Components	Manufacturer specified operating temperature range (worst cases)
Integrated circuits	-25°C to + 85°C
Capacitors and resistors	-55°C to + 85°C
Crystals	-40°C to + 90°C
Walkie-Talkie	-30°C to + 50°C
Batteries	-25°C (40% capacity) to + 60°C

FIGURE 4.22 - Temperature Operating Range for Slave Components

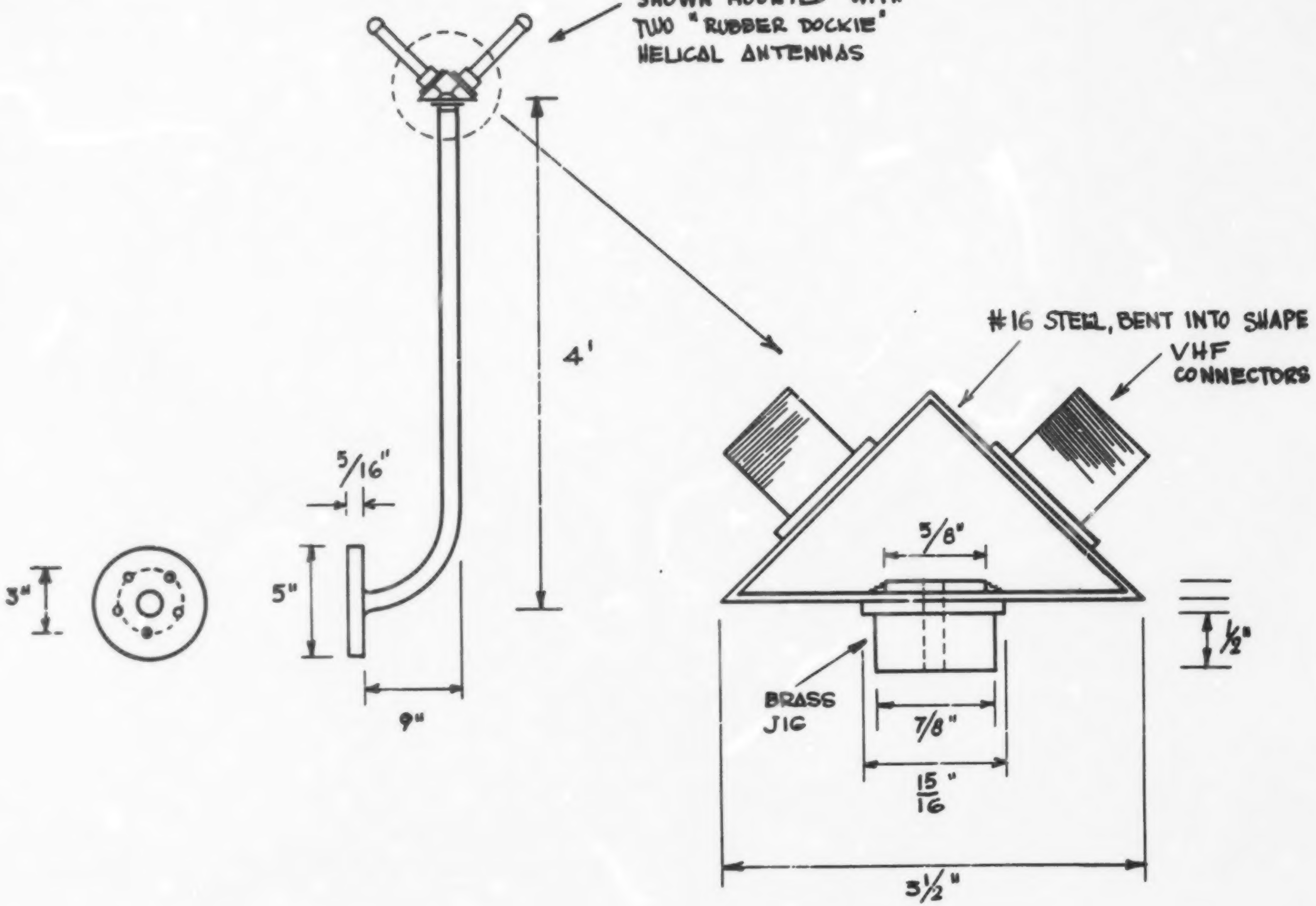

SHOWN MOUNTED WITH TWO "RUBBER DOCKIE" HELICAL ANTENNAS
4'
5/16"
3"
5"
9"
#16 STEEL, BENT INTO SHAPE
VHF CONNECTORS
5/8"
BRASS JIG
7/8"
15/16"
3½"
½"

Fig. 4.23: Slave Unit Antenna Mounts.

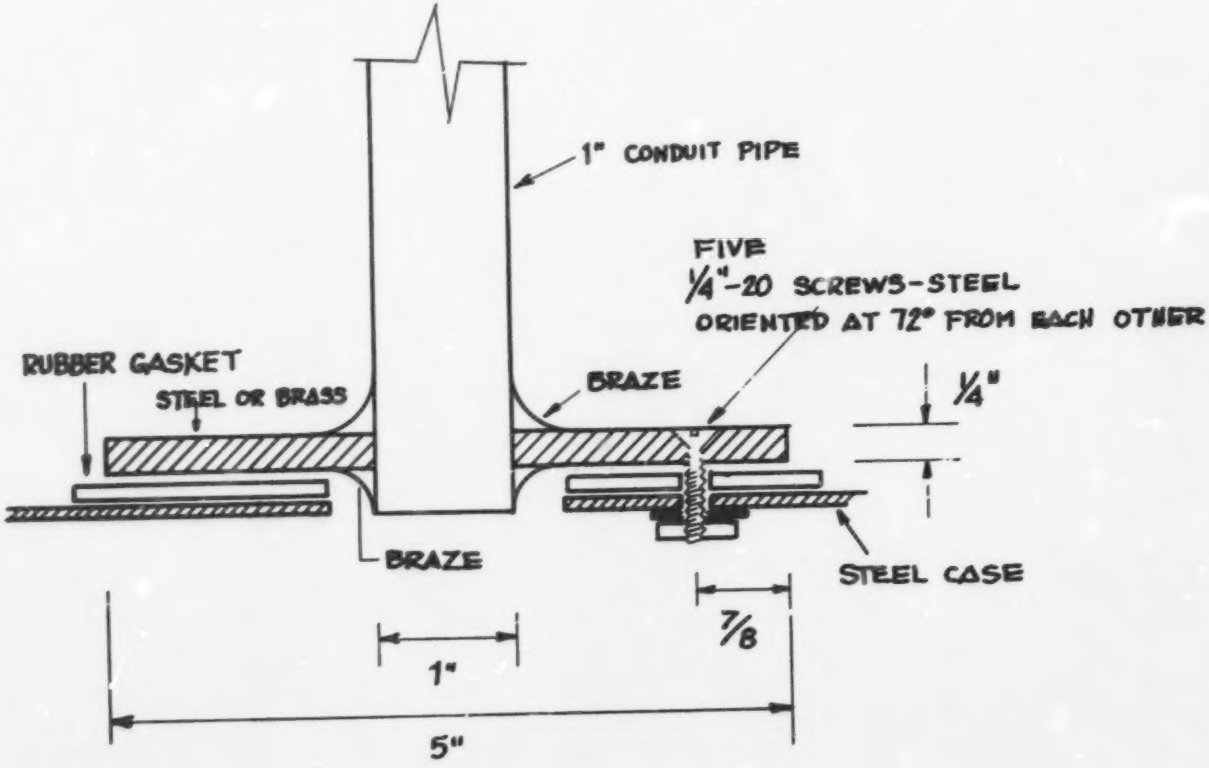


Fig. 4.24: Slave Unit Antenna & Enclosure Seal.

which interconnects the batteries, the transceivers, and the sensors to the MPCU box. The box contains the heart of the Slave unit, the MPCU circuit board (Fig. 4.25 to 4.27). Besides the electronic and circuit layout changes, several physical improvements were incorporated into the unit. The photograph in Figure 4.20 illustrates the packaging of the Electronics Assembly.

First, a double sided board with printed through holes was manufactured according to our layout by IJF Inc., a Toronto circuit board specialist company. The professionally made board, combined with the printed through hole technique, made for a simpler layout, and greatly increased board reliability. In addition, the board was tin plated, which will inhibit copper foil corrosion, tested for shorts, and coated with a special lacquer for preventing moisture leak through. Second, the internal wire harness was completely eliminated, as the 25 pin "D" type connector was mounted right on the circuit board. Next to it, another 25 pin male connector brings out desirable test points for the Slave Monitor. Both features will contribute to higher reliability, and easier servicing. In the same vane, and as with previous MPCU boards, no integrated circuit or transistor sockets were used during assembly of the board, and each solder connection was made with a grounded soldering station and was visually inspected for quality. The pointed circuit board is shown in the photograph of Figure 4.21.

Unlike with the first installation, the tiltmeters are now connected to the Slave unit through a 97 Series Connector, and can be rapidly disconnected and exchanged (Fig. 4.28). Both, the power, and the sensor input connectors on Box "A" are carefully mounted and sealed with silicone rubber to inhibit moisture leaks (Fig. 4.29 and 4.30).

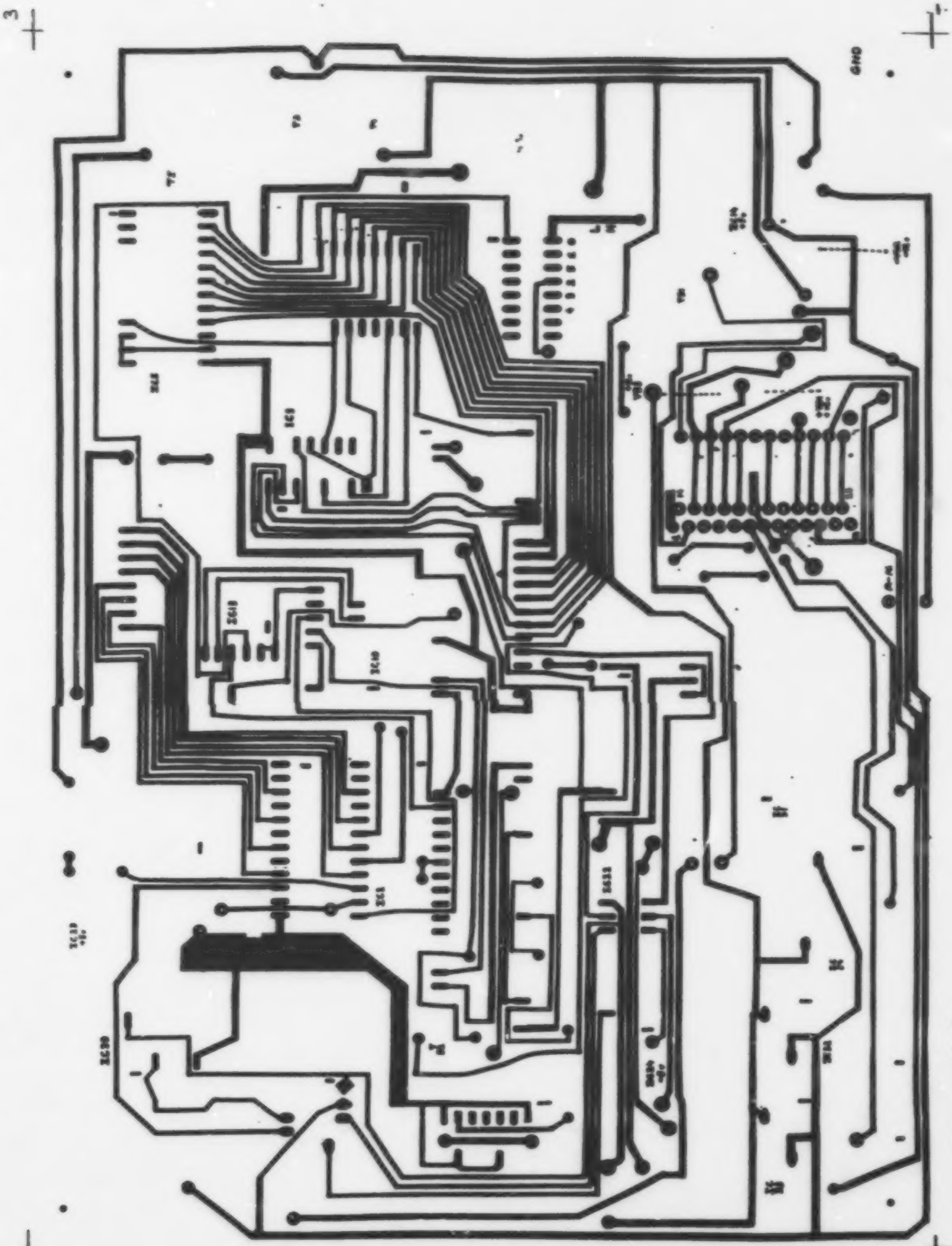


Fig. 4.25: MPCU Board Layout, Side A.

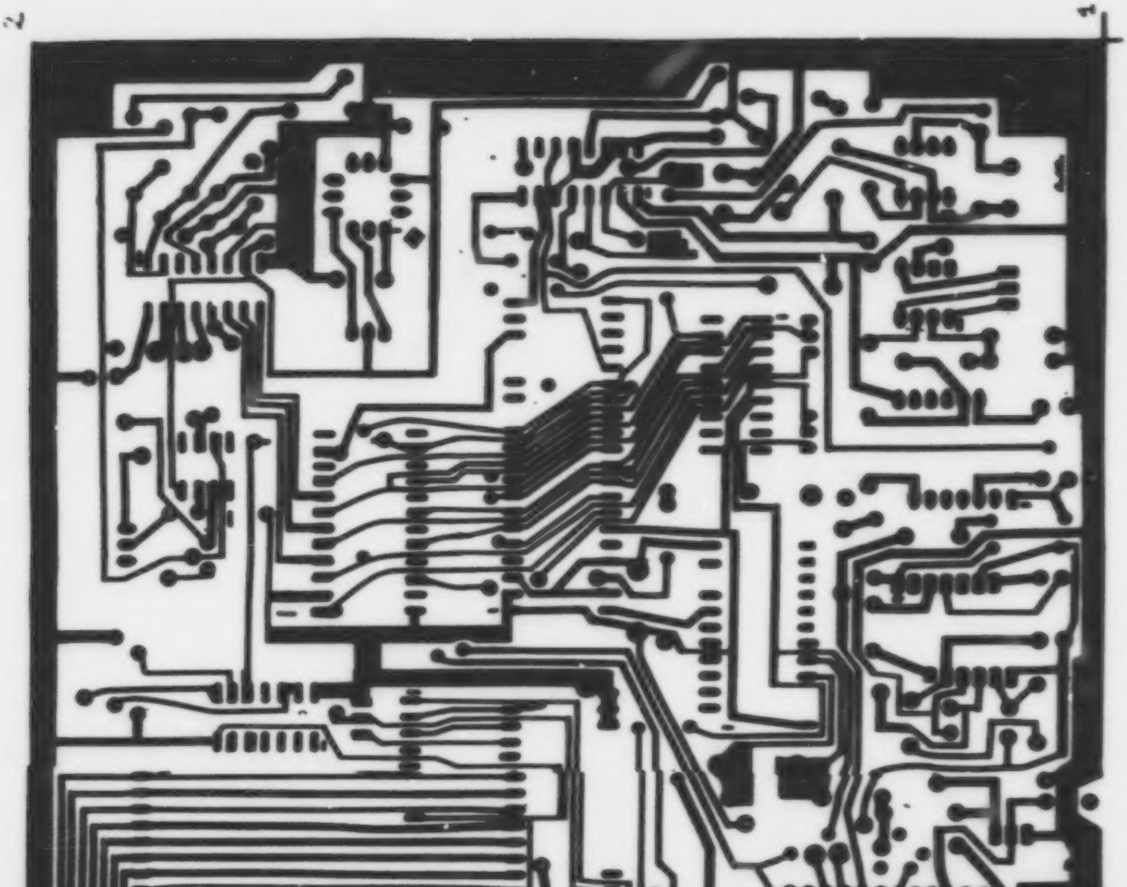


Fig. 4.26: MPCU Board Layout, Side B.

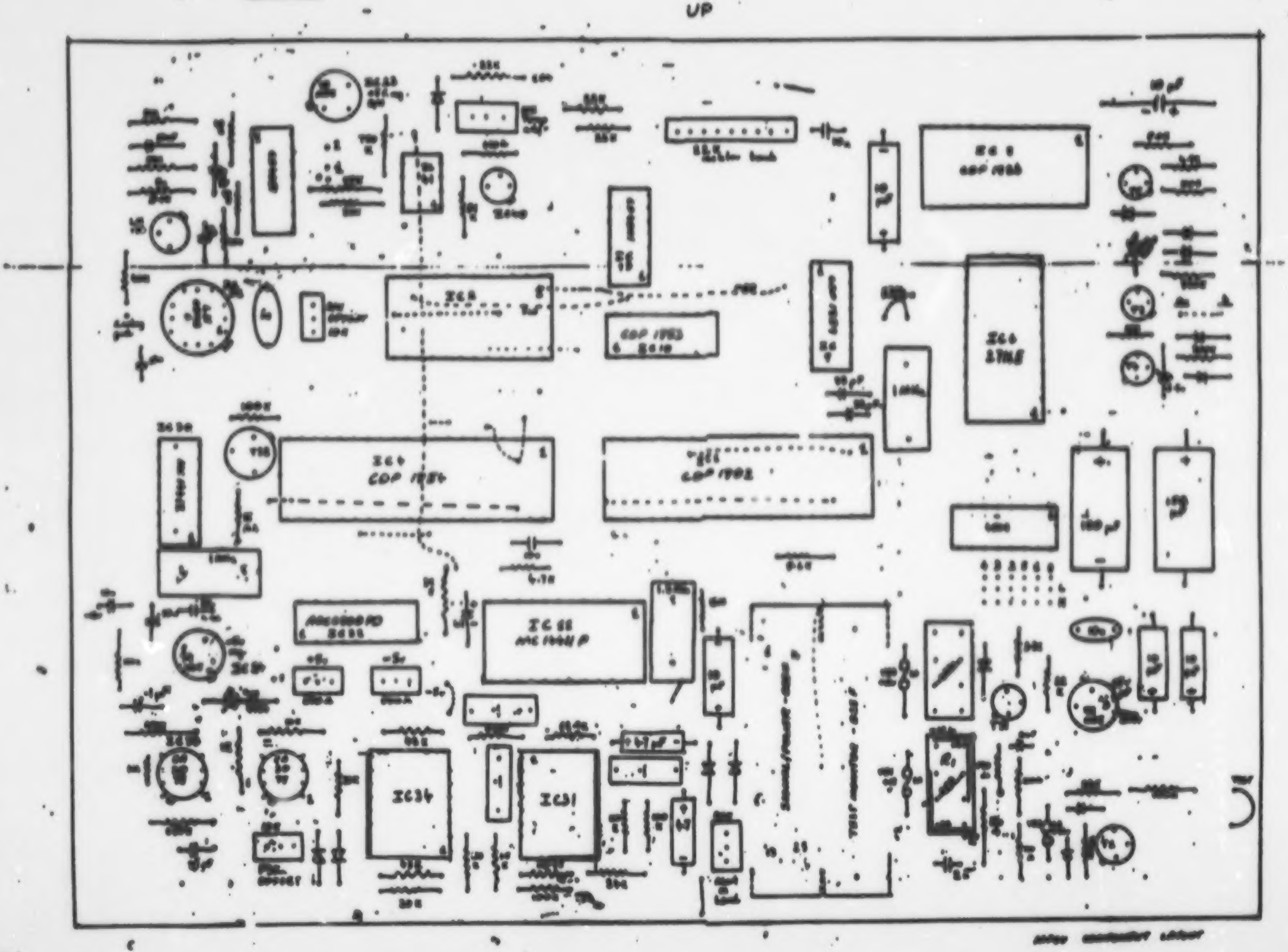
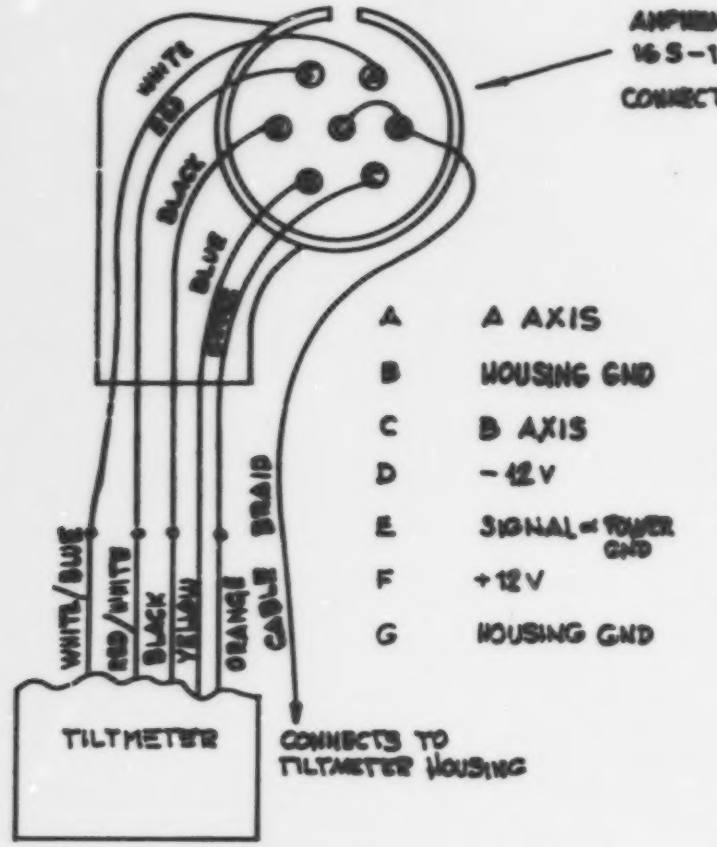
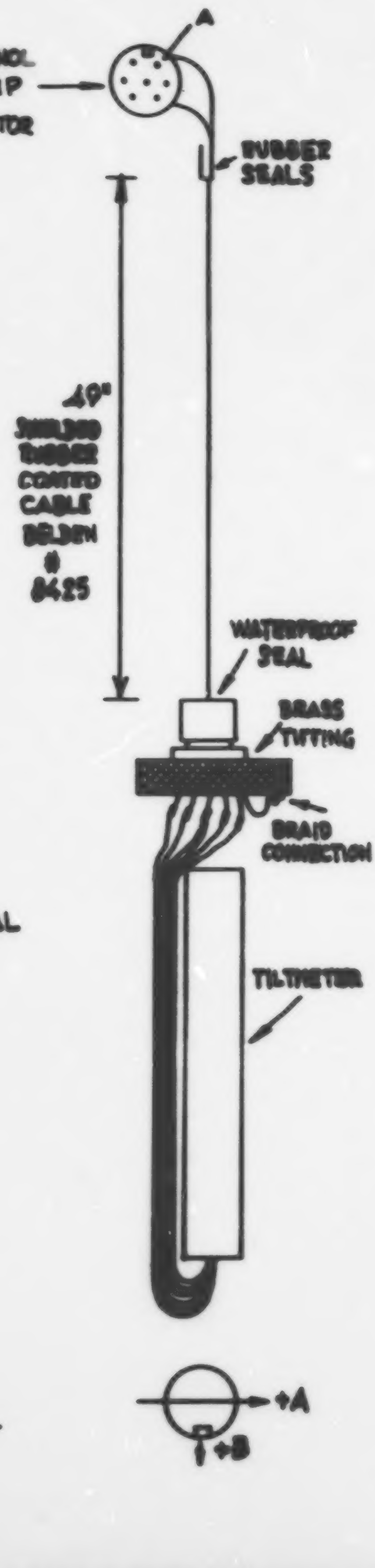


Fig. 4.27: MPCU Board Conponent Layout.

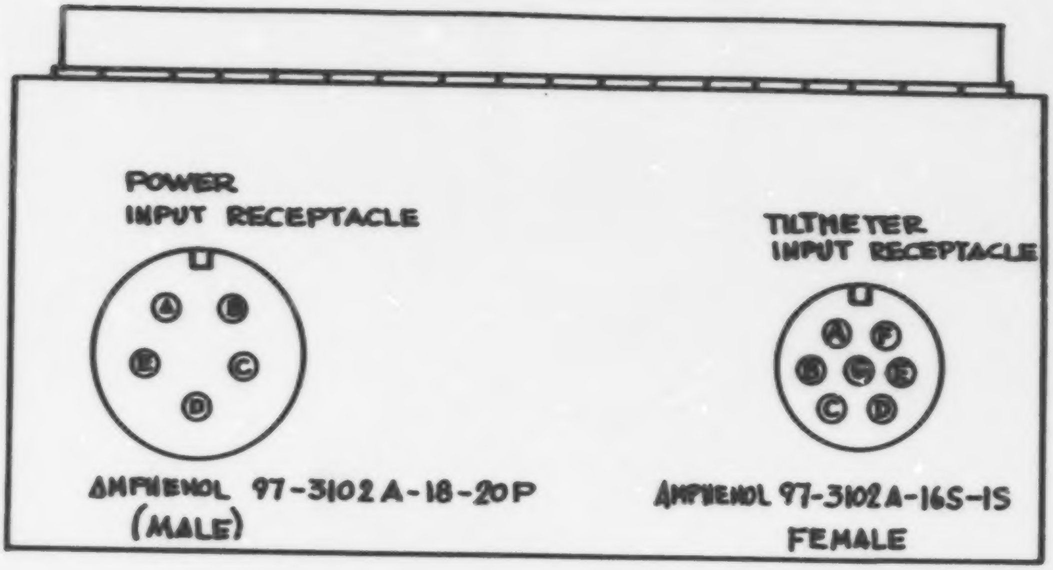


A	A AXIS
B	HOUSING GND
C	B AXIS
D	-12V
E	SIGNAL & POWER GND
F	+12V
G	HOUSING GND



NEW TERRA	OLD TERRA	FUNCTION
BLACK	BLACK	GND, POWER & SIGNAL
YELLOW	YELLOW	-12v
RED / WHITE	RED	+12v
ORANGE/WHITE	ORANGE	B AXIS
BLUE	BLUE	A AXIS

Fig. 4.28: Tiltmeter Connections.



A	VB1	+ 12V, 6 AM
B	VB3	+ 12V, 55 AM
C	COMMON, GROUND	
D	VB2	- 12V, 6 AM.
E	COMMON, GROUND	

POWER PLUG, FEMALE
AMPHENOL 97-3108 B-18-20S
CABLE CLAMP =
AMPHENOL 97-3057-1010-1

A	A AXIS
B	CONTAINER GROUND
C	B AXIS
D	-12V
E	POWER COMMON
F	+12V
G	CONTAINER GROUND

TILTMETER PLUG, MALE
AMPHENOL 97-3108 B-16S-1P
CABLE CLAMP =
AMPHENOL 97-3057-1008-1

Fig. 4.29: Slave Unit Power and Sensor Connectors.

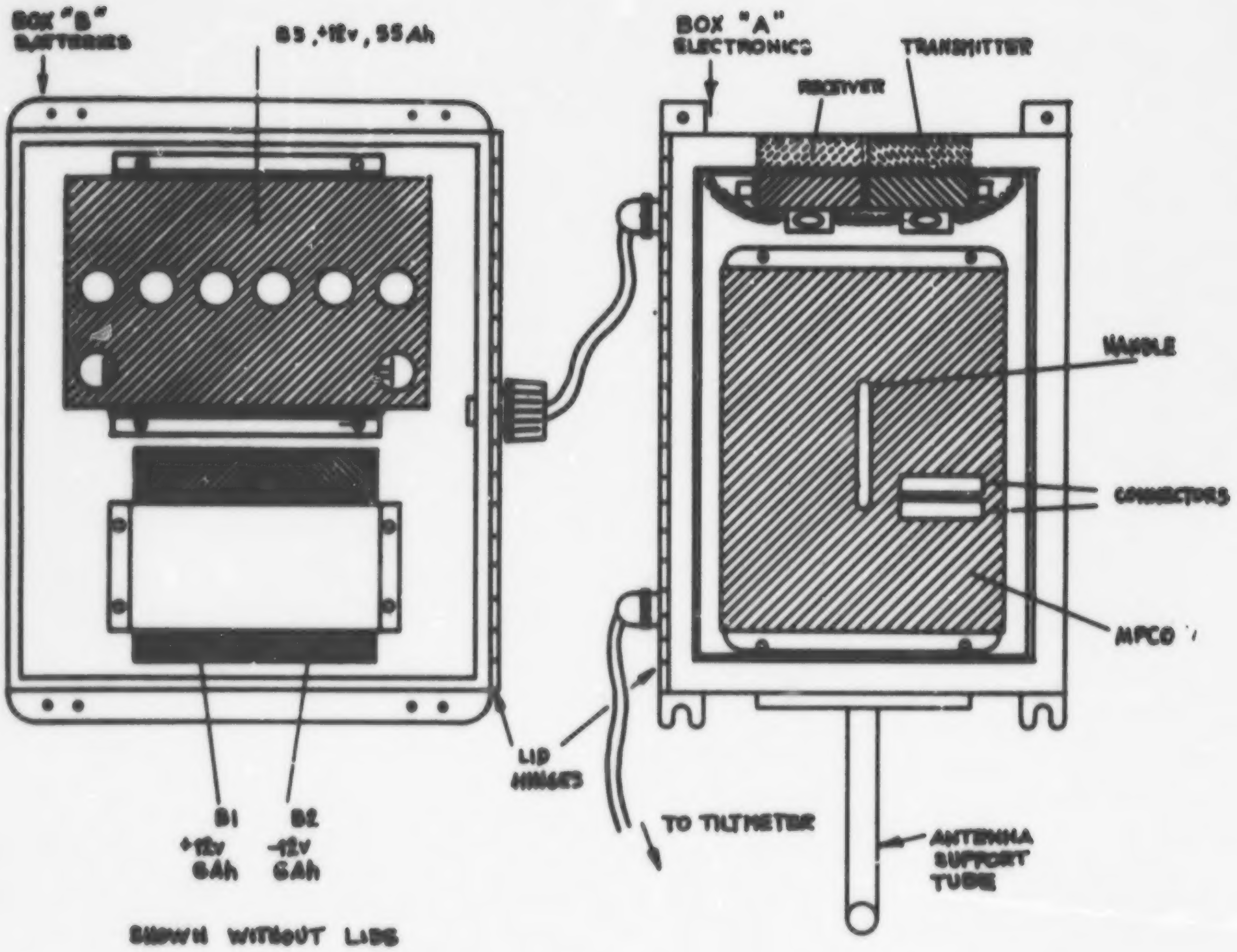


Fig. 4.30: Slave Unit Physical Component Layout.

In the case of the batteries, it was found that Lead-acid Gel-cells offered the best compromise in terms of operation at low temperatures, very low self-discharge, availability, and economy. These factors were confirmed during the first Slave system installation. Box "B" contains the three batteries and a harness which runs between them and the connector. VB1 and VB2 are firmly fixed with straps to the bottom platform of Box "B", while VB3 is wedged between steel angle plates and pieces of plywood. Handles on either side of the box fascilitate carrying.

Separating the electronics/link from the power supply, represented the most significant physical change in the Slave unit. Yet it was felt that battery replacement would be greatly simplified if all batteries could be scooped and hauled away for recharging in one quick trip. In this way the electronics remains untouched, and there is no need to use gasoline generators, and spend field time waiting for a full charge.

A Hammond 1414PH010 steel box, which conforms to CEMA/NEMA Type 12 specifications for an oil and dust tight enclosure, was used as Box "B", for housing the batteries. Another, a Hammond 1418N4B8, water tight, steel panel box (Box "A"), was used to house the MPCU/link boxes. The latter conforms to Canadian NEMA3, NEMA3R, NEMA12, and NEMA13 specifications for a dust-tight, oil-tight, water-proof, and sleet resistant box. The hinges and all external fastening hardware are made from stainless steel. Both boxes are painted with gray enamel. A short, rubber coated and steel braided cable connects the power box to the electronics box through a 97 Series connector which conforms to Military Specification MIL-C-5015, and both enclosures come with drilled tabs for mounting on a plywood or metal platform. See Fig. 4.31.

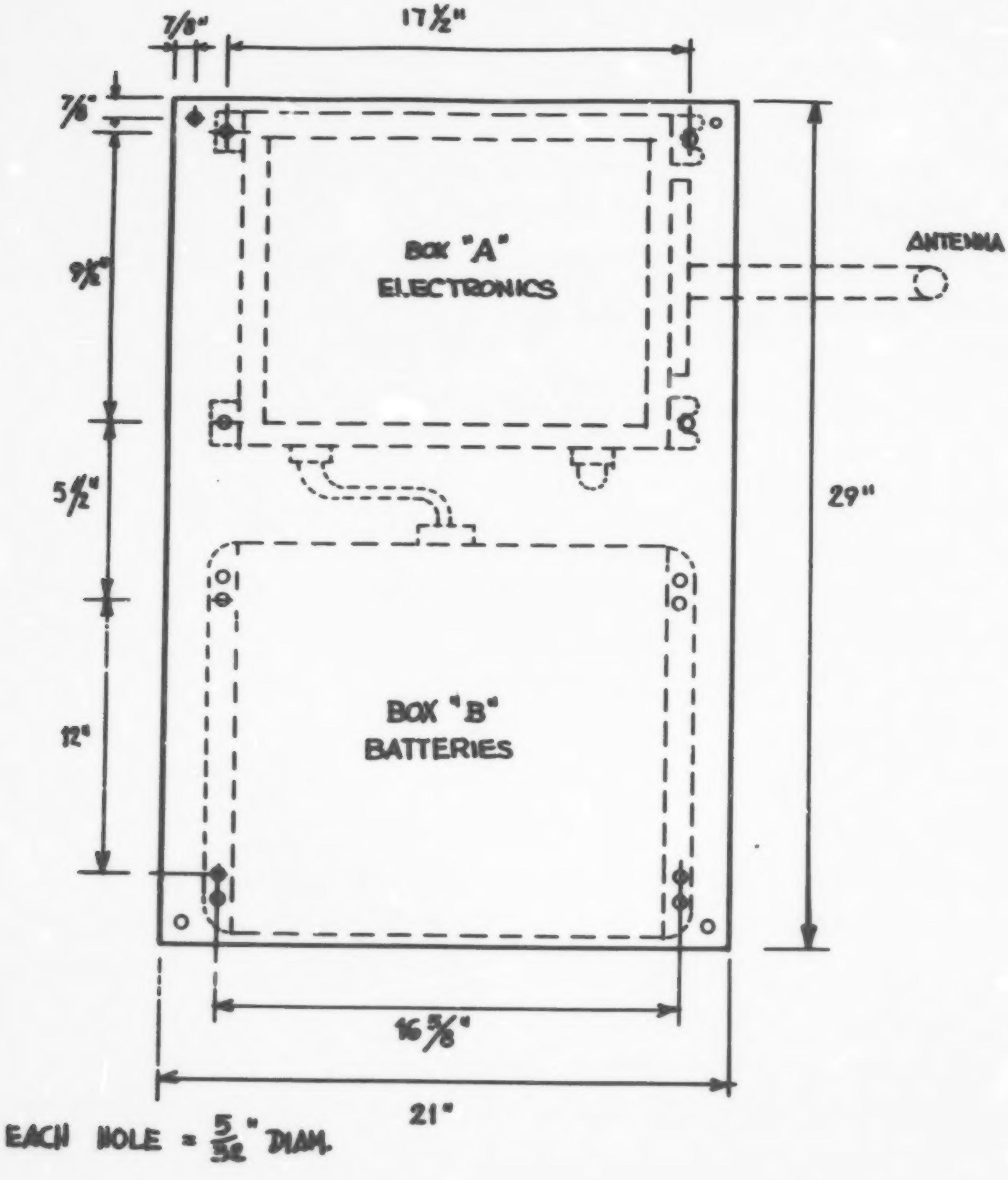


Fig. 4.31: Slave Unit Mounting Platform Dimensions.

4.7 Construction of the Master Unit

Since the Master station is operated from inside a building where 110V AC power is available, and no environmental extremes (temperature, rain, tampering, etc.) are expected, standard commercial electronic construction practices were employed.

The Master station consists of three basic units.

1) The IBM microcomputer and peripherals
2) A steel cabinet, housing the telemetry interface circuitry, the Repco transmitter/receiver link, and a 12 Volt, 1.5 A power supply.
3) A single, high gain, directional antenna.

In addition, a special cable connects the microcomputer to the interface cabinet, and a 50 Ohm coaxial cable feeds the external antenna.

The cabinet holding the interface circuitry was constructed from standard Hammond rack sections, and made to accomodate the links, the circuitry, and a small monitor speaker (Fig. 4.32). As was the practice with the Slave station, standard Repco link units were housed in separate die cast boxes, that can be easily removed from the main chassis. A special relay mounted on the back of the chassis, automatically switches the outdoor high gain directional antenna between the receiver input and transmitter output.

The interface circuitry was constructed on a single 12.5 x 17.5cm^2 Vector Plugboard using standard wire-wrap techniques. The board can be slid out for servicing, but is normally locked to the chassis with a retaining screw. A 44 pin edge socket and space were provided to accomodate another plugboard for possible future expansion. Unlike with the original Master unit, several status LED's, and monitor speaker volume adjustments were mounted on the new front panel, fascilitating its use and

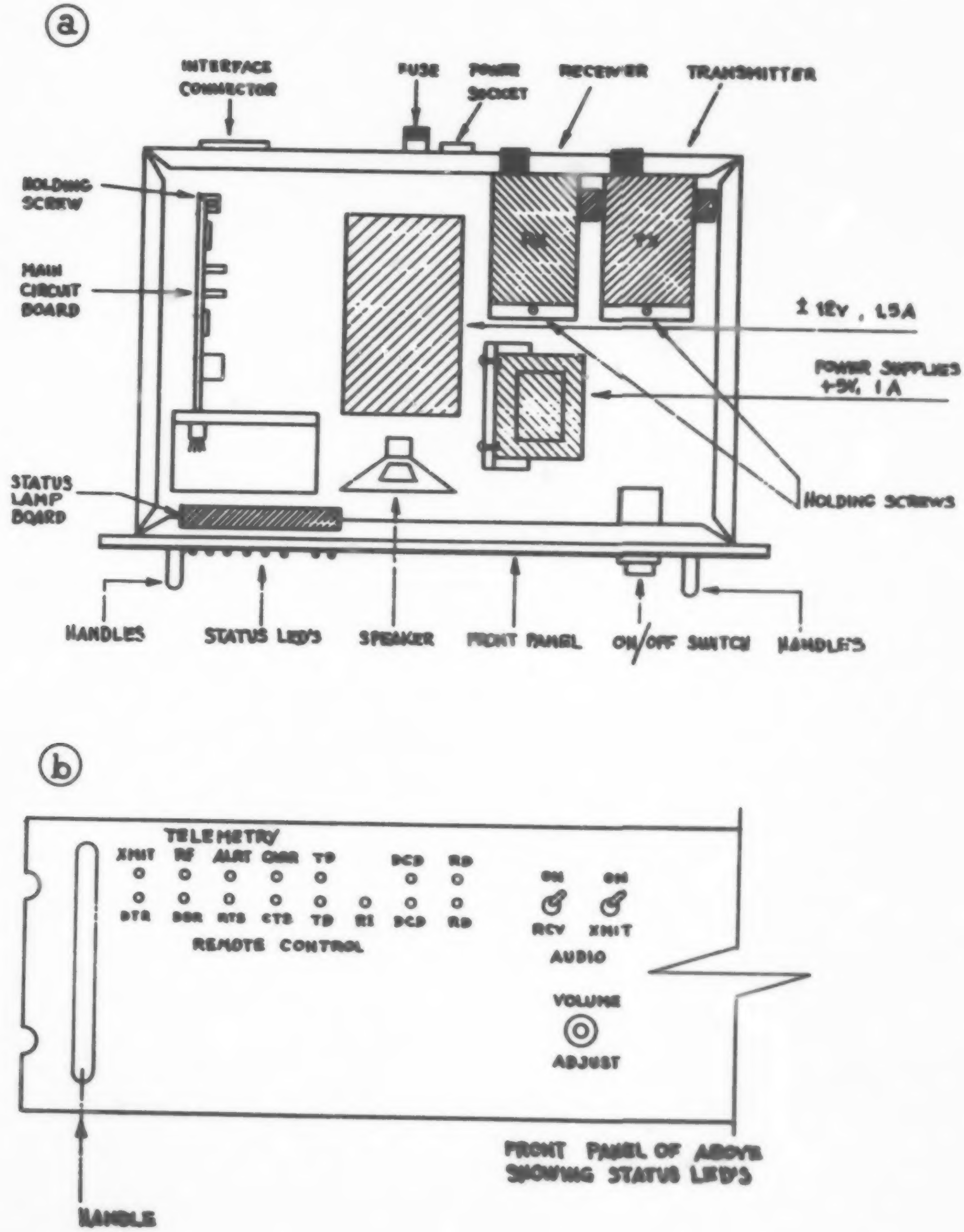


Fig. 4.32: a) Interface Unit; b) Front Panel Legends.

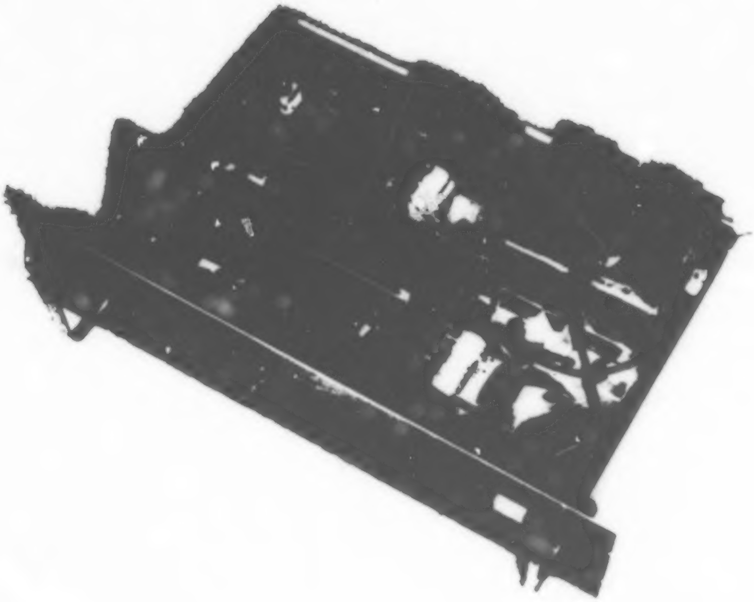


Fig. 4.33: Master Layout.

troubleshooting. The rear panel accomodates the power plug, the fuse, a "D" type microcomputer interface cable connector, and the UHF type antenna socket. Although a steel case houses the interface, the unit uses a 48 cm front panel and can be also mounted in a standard instrument.

4.8 Field Reconnaissance for the Installation of the Expanded Telemetry System

In June 1982, Dr. Chrzanowski together with Dr. Fisekci (the Scientific Authority) went to Sparwood to perform a preliminary reconnaisance for the future locations of the field stations of the expanded (8 field stations) telemetry system. The following alternative solutions had to be considered depending on the plans of the future mining operation in this area:

1) Four old stations #1, #2, #3 and #4 would remain in their present locations. The old station #0 and three new stations would be located along the crest of the Sparwood Ridge towards the top of the ridge, south east from the old stations. In this case one master station (in a new location on the west side) could control all the eight field stations with direct radio "intervisibility". Those locations would perhaps be satisfactory to monitor the first two years of the planned mining of sub-panel 06-200. In this case, the mining subsidence on the north-east slope would be monitored only by photogrammetry and ground surveys which would be difficult to perform due to the dense woods on that slope.

2) The second alternative was to leave the four old stations in their present locations, on the south-west slope, move station "0" to the top of the ridge and place the three new stations on the north-east slope. This distribution of the stations would give a better coverage for monitoring

the ground movements due to the extraction of panel 06-200 over the next 3-4 years. However, in this case, one master station could not handle all eight field stations unless a relay station would be set-up on top of the Sparwood Ridge. It was concluded that it would be more reliable and of equal cost to have two master stations on both sides of the slope rather than to have the relay station.

Due to some changes and uncertainties in planning the future extraction of panel 06-200, the final decision on the future locations of the expanded telemetry system could not be made until August 1983 when Dr. Chrzanowski together with Dr. Fisekci met with the management of Westar Mining Ltd. to discuss monitoring the exploitation of the sub-panels 06-200A and 06-200B. The discussion revealed, that Westar Mining would be interested in tilt monitoring only on the north-east slope (so-called "behind-the-ridge") where the conventional ground surveys could not be utilized for subsidence monitoring. The discussion was followed by a joint reconnaisance on the slope to select locations for the eight slave stations and for the master station. Figure 4.8 shows the field sketch of the selected sites for the eight tiltmeters and slaves. Sites No. 1 and 3 coincide with the present locations of the old telemetry system though the site No. 1 may require a 5-6 m high antenna in order to obtain the direct visibility to a new location of the master station. As far as the new location of the master station is concerned, three possible places have been found which should allow for almost direct visibility from the proposed locations of the eight stations, with only a few trees on the line of sight from stations 7, 8 and 9. The three possible locations of the master station are: the plant buildings of the open pit operation (distance ~ 6 km), an electric shop on the road to the open pit (distance ~

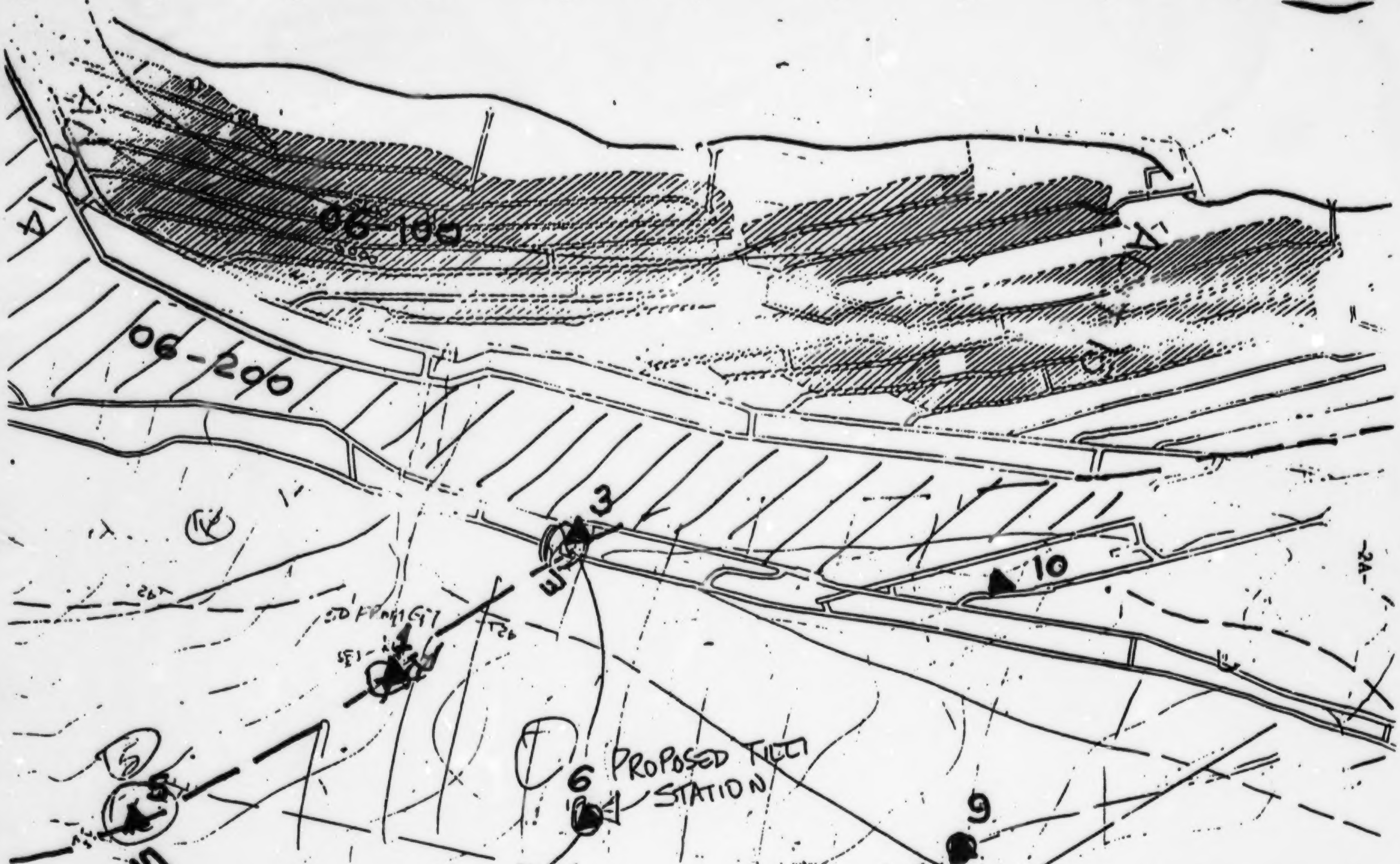


Fig. 6.34: Field sketch of the proposed location of the tiltmeter stations.

4 km) and a fan house down in the valley, about 3 km from the monitored slope.

The proposed locations of the tiltmeter stations should allow for detection of the subsidence limits (station #8) and should provide a reasonable picture of the time dependent development of the subsidence of the north-east slope.

According to the preliminary schedule, agreed with the Scientific Authority, the Consultants were supposed to install all eight tiltmeters during Dr. Chrzanowski's stay in Sparwood on August 28 to August 30, 1983. This was to be followed by the installation of the whole telemetry system in October, 1983. However, during discussions between Dr. Fisekci and the management of Westar Mining Ltd. on August 29 and 30, in the presence of Dr. Chrzanowski, it became clear that the mining authorities would prefer not to take on the responsibility for the maintenance of the telemetry system until late in summer of 1984. Their decision was based on the fact that due to a delay in the development work for sub-panel 6-200, no significant ground movement on the north-east slope is expected before the end of 1984. Therefore, the following decisions were made on August 30, 1983:

a) to postpone the installation of the telemetry system near Sparwood until August 1984.

b) to immediately dismantle the tiltmeters from the present stations 1, 2, and 4, and to take all eight tiltmeters back to Fredericton for additional research on their behaviour.

As already mentioned earlier, all the remaining tiltmeters were dismantled on August 30, 1983 and shipped to Fredericton for testing after three years of exposure to the difficult environmental conditions.

5. RESEARCH INTO THE TELEMETRY SYSTEM

The contract called for research into the design and development of a new Master station, the finalization and implementation of the telemetry system's remote control facility, a feasibility study and design of an "alarm" feature. The results of these research topics are presented in this chapter.

5.1 Purpose of a New Master Station

The Master unit represents the central data acquisition controller and serves as user interface. It originates Slave interrogation either automatically or under user control, receives the data from the Slaves, stores the data if required, and presents this data to the user in readable form. All communication with the Slave stations, including error recovery, is carried out internal to the Master unit without required user intervention.

The intelligence required to handle the above tasks in an automated manner without continuous user attention requires a computer based Master station. The basic approaches to the design of the Master were presented in great detail in the 1980 Final Report.

The new Master unit, denoted by Vers 2, exhibits the largest number of changes. In essence, the new Master is a completely redesigned module which has in common with the Vers 1 Master station only its telemetric operational principles. The redesign maintains full downward compatibility with the previous Vers 1 and Vers 1.1 telemetry systems.

5.2 Objectives

The new Master station Vers 2 was conceived with the following objectives in mind. A powerful computer is to be the heart of the Master which allows for an open-ended system approach to future expansion. A user friendly interface to the operator is to be provided through standard keyboard entry and a display monitor. This permits a large amount of simultaneous information to be presented to the operator which facilitates data examination and decision making. During unattended operating periods, all Slave data logged, along with relevant information, such as date and time, is to be saved on a hard copy printer and/or non-volatile mass storage device. This requirement avoids loss of data in cases of electric power failures, which were frequently experienced in past years. Due to these frequent power-downs, an automatic start-up mechanism is to be incorporated into the Master which restarts the telemetry operation after return of power under exactly the same conditions that existed before the accidental power-down. Access to the public network is to be provided which allows full remote control of all telemetric functions as well as data retrieval from any site with telephone connection.

The above described new features of the Ver 2 Master station represent a significant enhancement over the Vers 1 Master station. They can be achieved only by a more sophisticated computer system with more peripheral devices. In order to avoid an increase in the complexity of the custom- designed electronic circuitry of the Telemetry Interface, many of the new features are obtained by selecting and utilizing components which are integral parts of the computer system itself. This integrated approach leads to increased reliability of the new Master station. Indeed, the new Telemetry Interface is less complex than the former one used with the Vers 1 telemetry system (hardware reliability).

The telemetric operational functions are to be retained as described in the 1980 Final Report. Further enhancements affect the sensor data representation and diagnostic/maintenance procedures. An improved data analysis capability is to be provided by the new Master. The presentation of logged sensor data is to be in user units to eliminate time consuming conversion and offer greater information content (tilts in sec of arc, temperature in degrees, battery voltages in volts). Each set of logged data is to be accompanied by the date, time and error events during the interrogation. Maintenance statistics are to be maintained which record every detectable error for later diagnostic and trouble shooting.

The control software of the Vers 2 Master station is to be designed and coded with sufficient robustness and extensive error recovery, so that the telemetry system can operate unattendedly for long periods of time without failure (software reliability).

5.3 Hardware Design Principles

The hardware design of the Vers 2 Master station centers about the IBM-PC computer. This recent computer system offers the desired open-ended system approach. The computer system comprises the 128K RAM central processing unit, keyboard, monochrome display monitor with controller, hardcopy printer with controller, 160K SS-DD 5 1/4" diskette drive with controller, a non-volatile real-time clock/calendar, an asynchonous serial port for access to the public telephone network, and a parallel prt and asynchronous serial port serving as interface to the telemetry interface. The block diagram of the Master station is shown in Figure 5.1.

The Telemetry Module TELM exhibits a significantly reduced

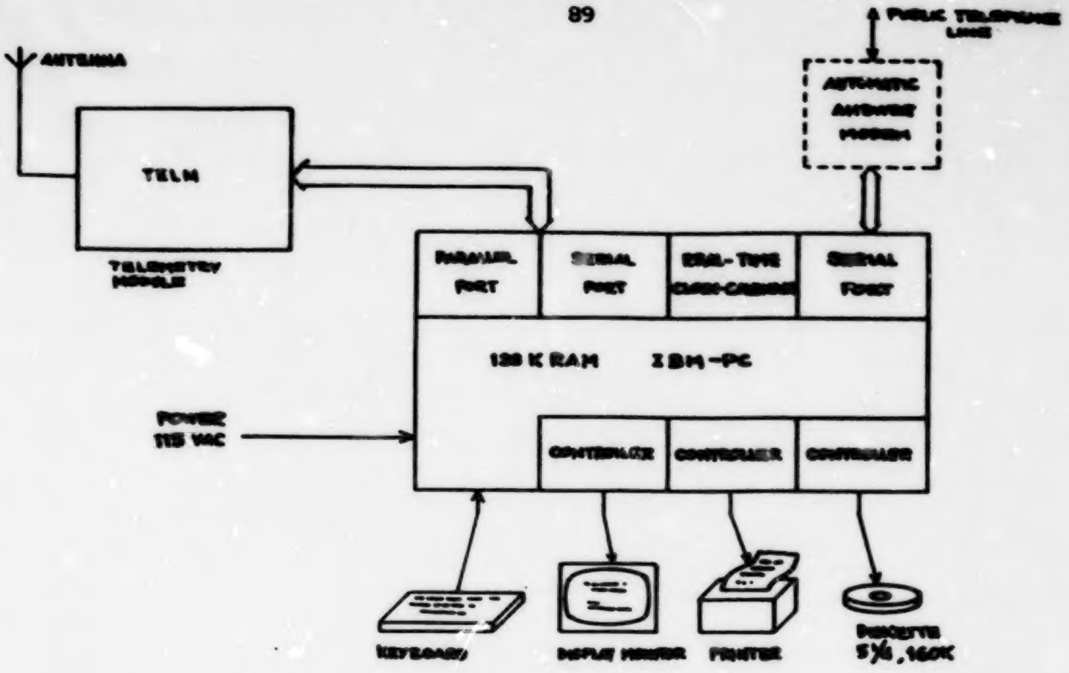


Fig. 5.1: Blockdiagram of Master Station (Vers 2)

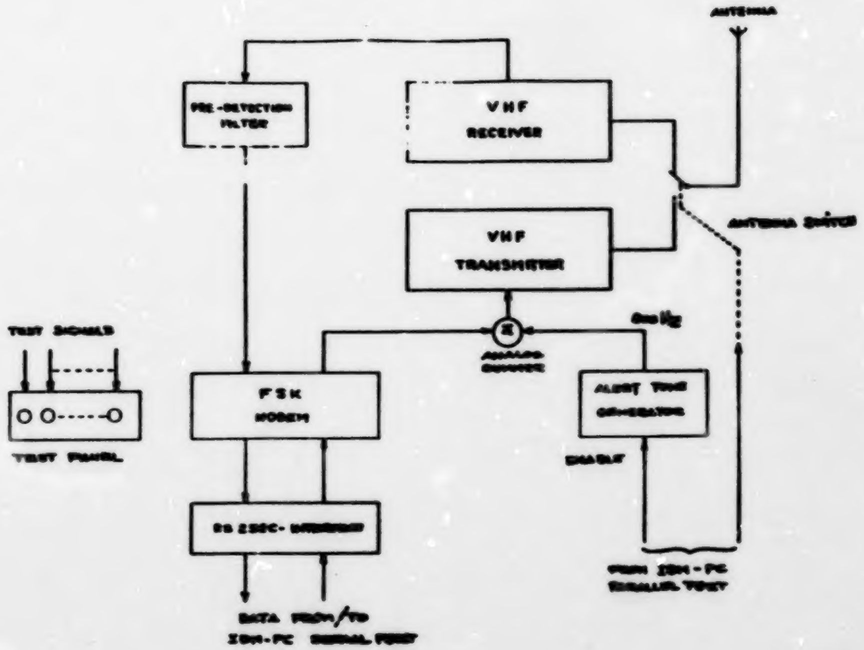


Figure 5.2: Blockdiagram of Telemetry Module TELM (Master Vers 2)

complexity as compared to the Vers 1 module. Figure 5.2 shows the block diagram of the TELM and reveals the close relationship with the Slave's telemetry module TLM, see Figure 2.1. The module is equipped with the new VHF REPCO transmitter/receiver devices, Figure 5.3. The pre-detection filter, shown in Figure 5.4, cleans any noisy received signal for increased data transmission reliability. The antenna switch permits the use of a single directional antenna for better VHF transmission/reception in mountainous areas, reducing the effect of radio-wave reflections (1980 Final Report, Section 4.20). The Alert tone generator generates a 800 Hz tone which is transmitted to all Slaves as a "wake-up" signal. The serial asynchronous digital data to/from the FSK modem passes through an interface adapter which makes it compatible with the computer's serial interface peripheral. The computer's parallel port controls the VHF receiver/ transmitter operation as well as the antenna switch, and the Alert tone generator.

The Telemetry Module TELM contains a small test monitor with indicator lights in lieu of a Test Monitor as used with the Slaves. The status of the illuminated indicator lights reflect the internal sequence of activities during Slave interrogations and aids in field maintenance and error diagnostic.

5.4 Circuit Description of New Master

The circuit diagram of the Vers 2 telemetry module TELM is shown in Figure 5.5. The basic circuit description which appears in the 1980 Final Report holds for this module as well. In addition, the following comments will point out some differences.

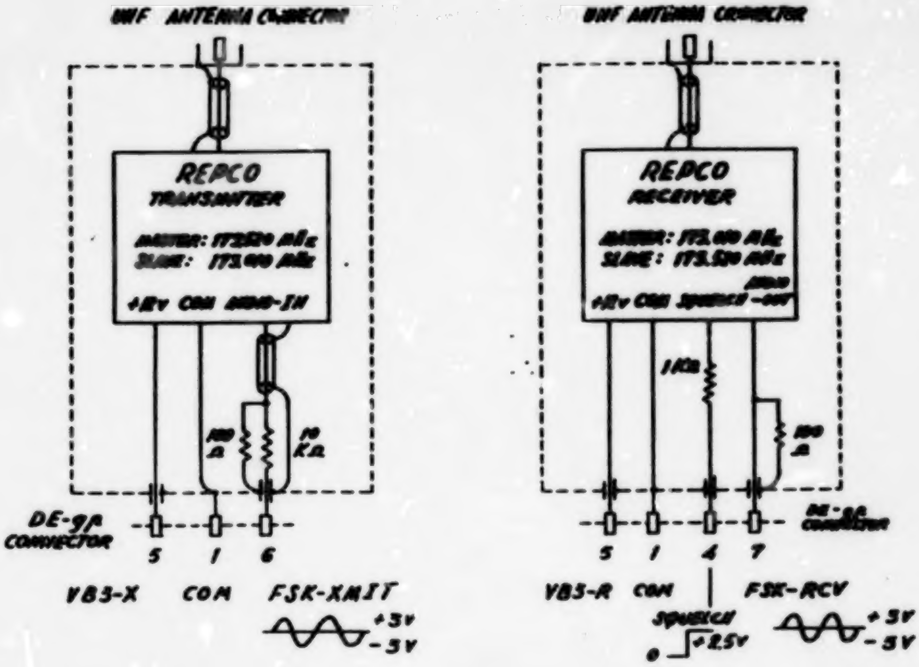


Fig. 5.3: VHF Transmitter and Receiver Modules (Master Vers 2)

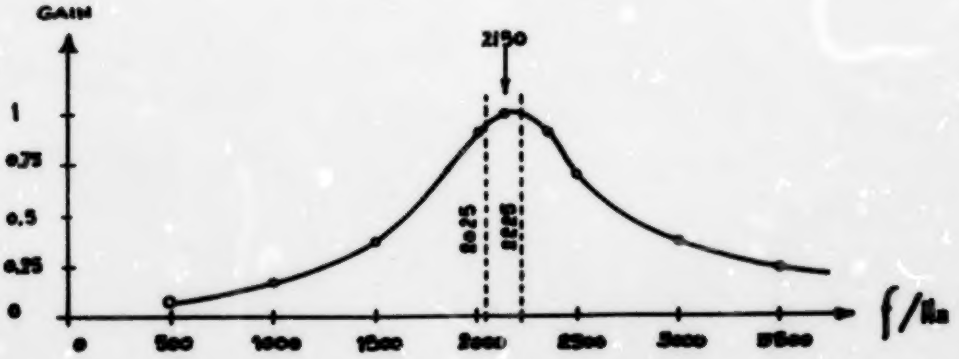


Fig. 5.4: Frequency Response of Pre-Detection Filter (Master Vers 2)

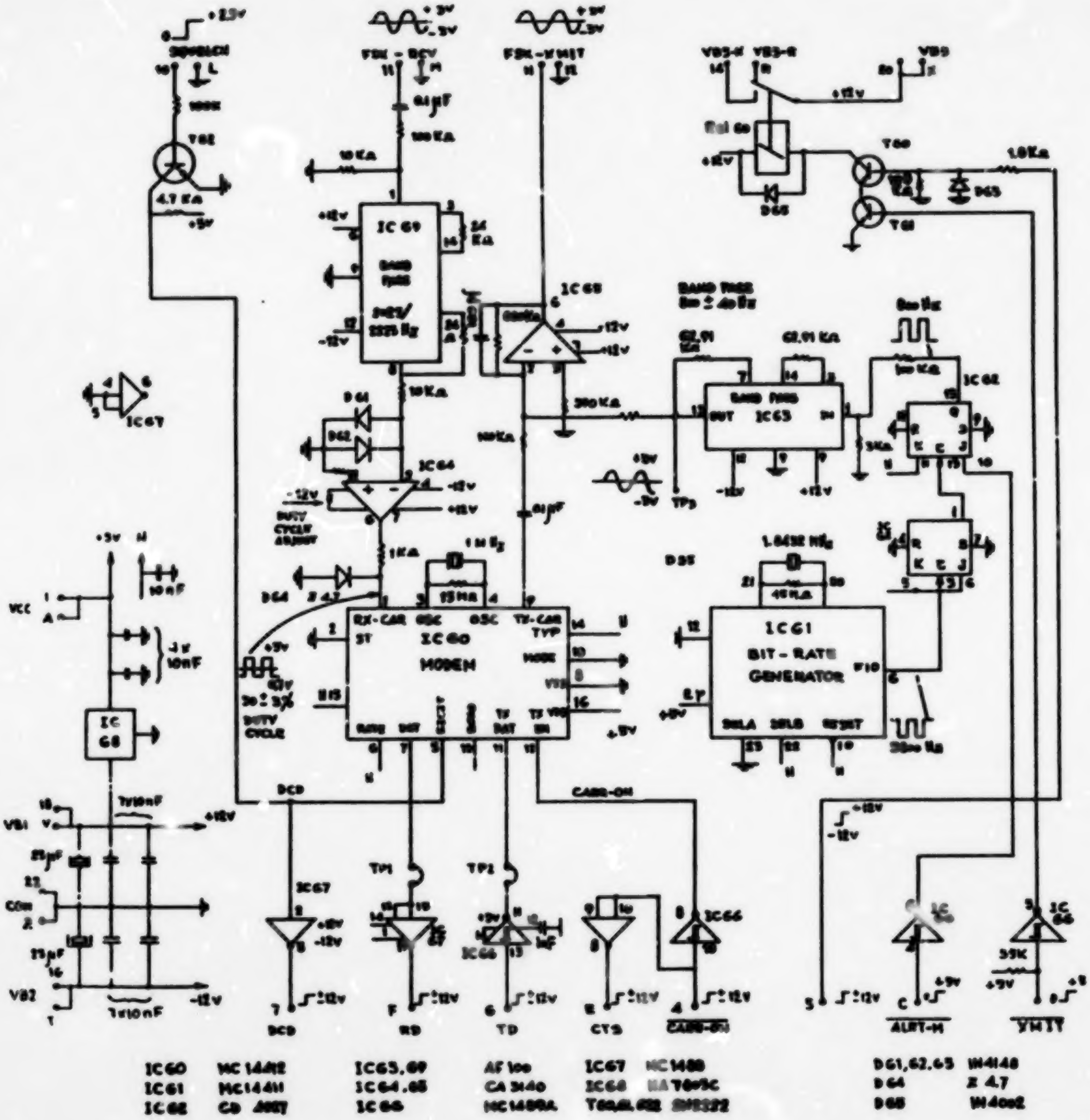


Fig. 5.5: Telemetry Module TELM (Master Vers 2)

The IBM-PC's serial port is RS232C compatible. The voltage level converter IC66, IC67 adapt the module's 0/5V TTL-compatible logic to the -12/+12V logic of the EIA RS-232C standard. In order to prevent the VHF transmitter from sending in an uncontrolled manner when the telemetry's control program is not yet running in the IBM-PC (during power-up), transister T60 inhibits the receiver/transmitter power switching relay Rel 60 which powers the VHF transmitter (VB3-X), as RTS is off (-12V) during this period.

5.5 Control Software for New Master

The Master's control software provide the environment in which real-time processing can take place in an efficient way. The software is fully modularized to facilitate the development, debugging and future additions. Each module supports a particular function and is described individually in this section. During the research into the objectives and suitable approaches, as well as into the appropriate design of the control software, particular emphasis was focussed on a user-friendly operator interaction, highest data security and robust software operation with powerful automatic error recovery (software reliability). Unattended operation for a long period of time is therefore possible.

5.5.1 Objectives

The modular architecture of the Master control software (Vers 2) is illustrated in Figure 5.6. The objectives were selected with a view towards versatility in operation and ease of operation by the user. The selected features are highlighted below. The features are grouped to indicate the software modules which implement them.

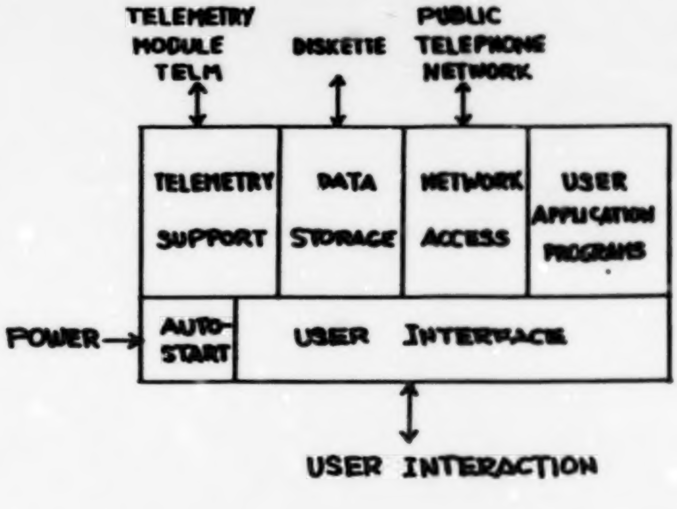


Fig. 5:6: Modular Architecture of Master Software (Vers 2)

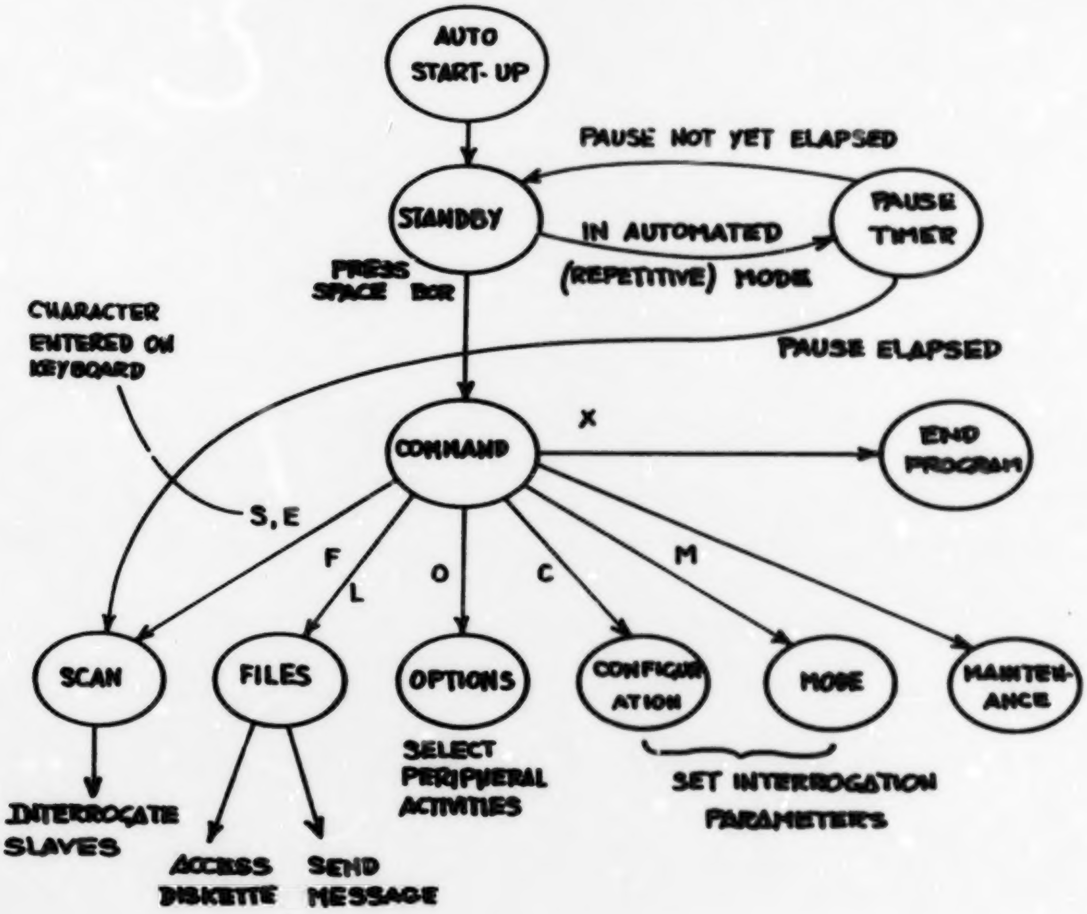


Fig. 5.7: State Diagram of Master Operation (Vers 2)

(p) Storage of currently active system configuration and parameters on diskette.

Network Access:

(q) Access to public telephone network for remote control purposes using standard interfacing techniques;

(r) Remote control of all telemetry functions;

(s) Retrieval and transfer of data stored on diskette to remote location;

(t) Transfer of maintenance data to remote location for remote system diagnostic (e.g., in Fredericton);

(u) Exchange of messages between Master and remote location to facilitate local system maintenance (e.g., in Sparwood) assisted by personnel at the remote site (e.g., in Fredericton).

Auto Start-Up:

(v) The currently active system configuration and parameters are held on diskette in a start-up file;

(w) Automatic start-up after a power-failure with the telemetry system in the same state as prior to the failure and resuming its operation: unattended operation is possible.

5.5.2 Approach and Software Design Principles

The design of the individual software modules and the implications are briefly outlined. The state diagram depicted in Figure 5.7 reveals the interactions between the modules.

After power-on, the program reads the previously used system parameters from the start-up file on diskette and resumes operation, entering the stand-by mode. If the repetitive interrogation mode was previously selected, the Slave interrogation is resumed, otherwise user

User Interface:

(a) Fully menu-driven to facilitate the successful use by novice users;

(b) Error recovery of operator entry errors by the operator;

(c) Presentation of sensor data in user units (tilts in sec of arc, temperature in degrees, battery voltages in volts);

(d) Presentation of interrogation events (date, time, error log) to permit quick user orientation for long-time interrogation results;

(e) Presentation of a summary of the maintenance statistics to permit maintenance and quick diagnostic of problems;

(f) Listing of sensor data and maintenance data on printer, upon request.

Telemetry Support:

(g) User selection of the configuration of a set of Slaves involved in the interrogation;

(h) User selection of the interrogation mode (single or repetitive, i.e., automated);

(i) User selection of the interrogation interval in automated mode;

(j) Slave interrogation is fully automatic without operator attention;

(k) Fully automated error detection and recovery by retransmission requests;

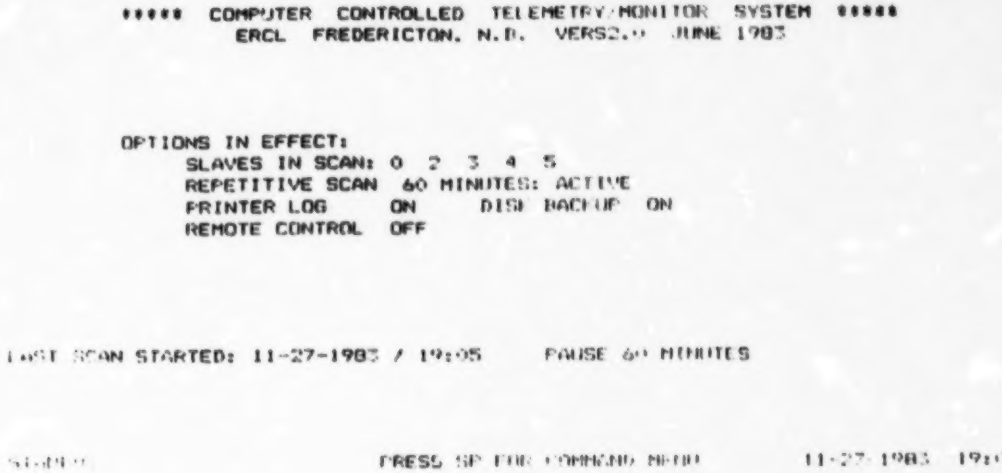
(l) maintenance data is updated upon every interrogation event;

(m) User selection of recording events, such as data storage on diskette and/or printer.

Data Storage:

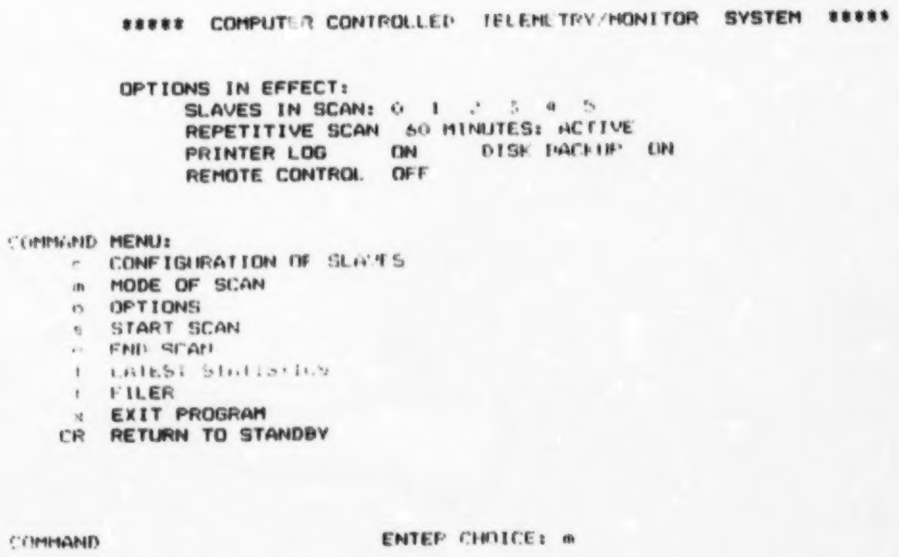
(n) Back-up storage of sensor data and maintenance data, along with interrogation events (date, time, error log) on diskette;

(o) Data is protected from accidental loss due to power or computer failure;



```
***** COMPUTER  CONTROLLED  TELEMETRY/MONITOR  SYSTEM *****
         ERCL  FREDERICTON, N.B.  VERS2.0  JUNE 1983



     OPTIONS IN EFFECT:
          SLAVES IN SCAN: 0  2  3  4  5
          REPETITIVE SCAN  60 MINUTES: ACTIVE
          PRINTER LOG      ON      DISK BACKUP  ON
          REMOTE CONTROL  OFF



LAST SCAN STARTED: 11-27-1983 / 19:05     PAUSE 60 MINUTES



STANDBY                PRESS SP FOR COMMAND MENU        11-27-1983  19:07
```

Fig. 5:8: Stand-by Menu



```
      *****  COMPUTER CONTROLLED  TELEMETRY/MONITOR  SYSTEM  *****

      OPTIONS IN EFFECT:
           SLAVES IN SCAN: 0  1  2  3  4  5
           REPETITIVE SCAN  60 MINUTES: ACTIVE
           PRINTER LOG      ON      DISK BACKUP  ON
           REMOTE CONTROL  OFF


COMMAND MENU:
      c   CONFIGURATION OF SLAVES
      m   MODE OF SCAN
      o   OPTIONS
      s   START SCAN
      e   END SCAN
      l   LATEST STATISTICS
      f   FILER
      x   EXIT PROGRAM
     CR   RETURN TO STANDBY


COMMAND                      ENTER CHOICE: m
```

Fig. 5:9: Command Menu

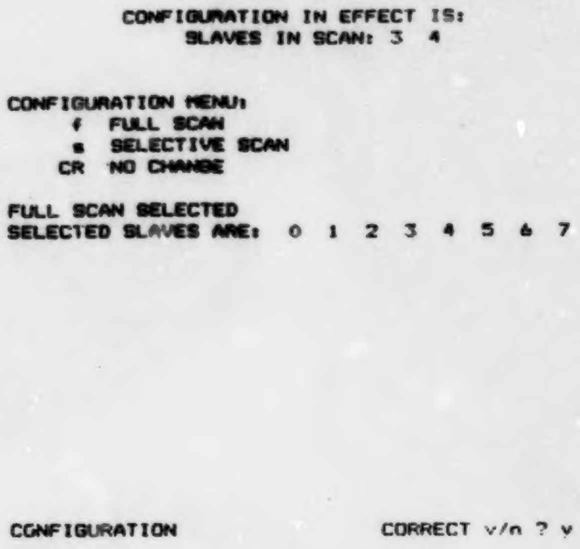
intervention is required to activate further actions. In stand-by mode, the remote control of telemetric operations can be carried out, if enabled.

User interaction with the Master takes place in form of menus for prompts and subsequent user replies. This approach achieves successful operations even by novice users who are unfamiliar with the system, as all commands are listed in the menu and all replies are tested for validity. Up to four hierarchical levels of menus are implemented.

In the Stand-by mode, the user is informed about the current system parameters and he enters the Command mode by pressing the space bar. The Stand-by menu is shown in Figure 5.8.

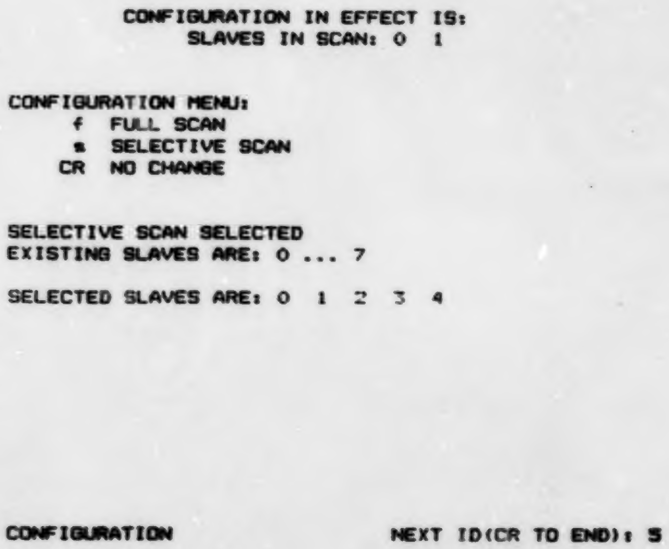
In the Command mode, the user can exercise full control over the telemetry system's operation. Interrogation parameters can be altered, a scan can be started or ended, and sensor data stored on diskette can be retrieved for examination and printing. During the command mode execution, the automated interrogation cycle and the remote control facility is temporarily suspended. The command menu is shown in Figure 5.9. It represents the second level of menus where the user specifies the action to be taken. Any one of eight functions can be selected which cause another menu to appear on the screen if additional information is to be provided by the user. The latter menus are the third hierarchical menu levels and are discussed separately for each function.

If the Configuration mode is selected, either one of two menus shown in Figure 5.10 and 5.11 appears on the screen depending upon the selection of a full scan or selective scan of Slaves. The purpose of this function is to permit the user to construct a set of Slaves which are involved in subsequent scans. Any combination of existing Slave stations is allowed. In the selective configuration mode, the user enters the



```
               CONFIGURATION IN EFFECT IS:
                    SLAVES IN SCAN: 3  4

     CONFIGURATION MENU:
          f  FULL SCAN
          s  SELECTIVE SCAN
         CR  NO CHANGE

     FULL SCAN SELECTED
     SELECTED SLAVES ARE:  0  1  2  3  4  5  6  7




     CONFIGURATION                  CORRECT y/n ? y
```

Fig. 5.10: Configuration Menu (Full Scan)



```
               CONFIGURATION IN EFFECT IS:
                    SLAVES IN SCAN: 0  1

     CONFIGURATION MENU:
          f  FULL SCAN
          s  SELECTIVE SCAN
         CR  NO CHANGE

     SELECTIVE SCAN SELECTED
     EXISTING SLAVES ARE: 0 ... 7

     SELECTED SLAVES ARE: 0  1  2  3  4




     CONFIGURATION                  NEXT ID(CR TO END): 5
```

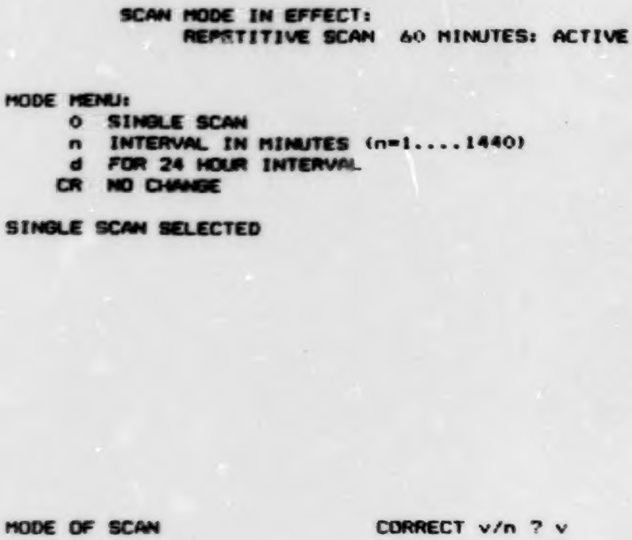
Fig. 5.11: Configuration Menu (Selective Scan)

desirable Slave identifier ID (0,1,2,...) on the keyboard (fourth hierarchical menu level), whereas in the full configuration mode this set includes all existing Slaves and is automatically generated.

The telemetry system's Scan mode is selected via the Mode-of-Scan menu, Figure 5.12 and 5.13. The user either selects a single scan or a repetitive (automated) scan which is repeated at specified intervals, from 1...1440 minutes. The frequently used 24 hour default interval can readily be selected. This mode selection defines the mode parameters only, but does not initiate a scan. Once started, the repetitive scan continues (even after resumption of operation after a power failure) until ended by the operator.

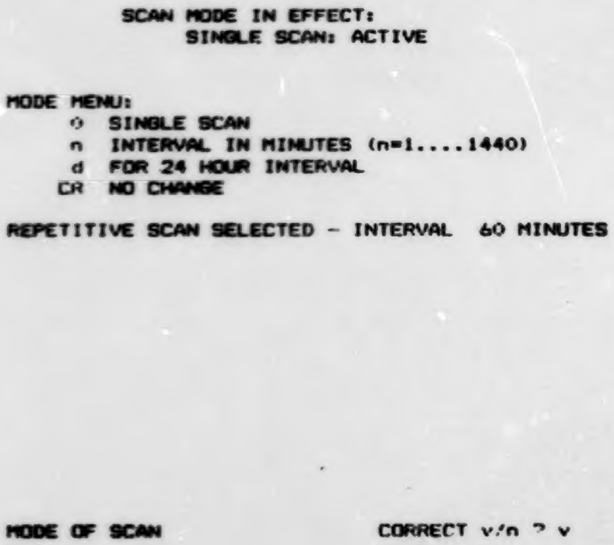
The Option menu permits the user to enable/disable auxiliary computer peripherals. Recording of sensor and maintenance data can take place on the printer and/or the diskette. The remote control facility can also be inhibited if external access is undesirable, e.g., during maintenance sessions. The selected options remain in effect (even after restarting the system after a power-down) until changed. The pertinent menu is illustrated in Figure 5.14.

The Filer is a powerful software package which permits the user to retrieve sensor and/or maintenance data from the diskette, transfer it to the display screen for examination or to the printer for listing. Data can be deleted if so desired, however, a dual-response is required to prevent accidental loss of data due to operator errors. In addition, a message can be sent to the remote location via the telephone access. Either one of three fourth level menus may appear on the screen. The menu covering the retrieval of back-up files stored on the diskette is shown in Figure 5.15. The user specifies the type of information (sensor and/or maintenance data)



```
              SCAN MODE IN EFFECT:
                   REPETITIVE SCAN  60 MINUTES: ACTIVE


    MODE MENU:
         0  SINGLE SCAN
         n  INTERVAL IN MINUTES (n=1....1440)
         d  FOR 24 HOUR INTERVAL
        CR  NO CHANGE

    SINGLE SCAN SELECTED








    MODE OF SCAN                    CORRECT y/n ? y
```

Fig. 5.12: Scan Mode Menu (Single Scan)



```
              SCAN MODE IN EFFECT:
                   SINGLE SCAN: ACTIVE


    MODE MENU:
         0  SINGLE SCAN
         n  INTERVAL IN MINUTES (n=1....1440)
         d  FOR 24 HOUR INTERVAL
        CR  NO CHANGE

    REPETITIVE SCAN SELECTED - INTERVAL  60 MINUTES








    MODE OF SCAN                    CORRECT y/n ? y
```

Fig. 5.13: Scan Mode Menu (Repetitive Scan)

```
          OPTIONS IN EFFECT:
               PRINTER LOG      ON       DISK BACKUP  OFF
               REMOTE CONTROL  OFF

OPTION MENU:
       pon  PRINTER LOG ON
      poff  PRINTER LOG OFF
       don  DISK BACKUP ON
      doff  DISK BACKUP OFF
       ron  REMOTE CONTROL ON
      roff  REMOTE CONTROL OFF
        CR  NO CHANGE

DISK BACKUP  ON




OPTIONS                      ENTER CHOICE: ron
```

Fig. 5.14: Option Menu

```
FILER MENU:
      t  TRANSFER BACKUP FILE
      d  DELETE BACKUP FILE
      m  SEND MESSAGE TO REMOTE
     CR  RETURN

TYPE OF DATA:
      s  SENSOR DATA ONLY
      m  MAINTENANCE STATISTICS ONLY
      a  ALL OF THE ABOVE

SPECIFY TIME PERIOD OF DATA:
      STARTING DATE, OR CR FOR EARLIEST DATE
      ENDING DATE, OR CR FOR LATEST DATE
          (DATE FORMAT: MM-DD-YYYY)

SENSOR DATA AND MAINTENANCE STATISTICS FROM 11-20-1983 TO 11-30-1983
   TO BE TRANSFERRED FROM DISK TO SCREEN AND PRINTER


FILER                        CORRECT y/n ? y
```

Fig. 5.15: Filer Menu

and the period of time for which the data is to be retrieved. This data is displayed on the screen, and listed on the printer if the printer-log-on option is in effect.

The Scan mode is entered when selected, to either start or end a scan activity. The scan action initiates interrogation of the Slaves as prescribed by the previously selected interrogation parameters. All error detection and recovery takes place without the need for user intervention. The results of the scan are displayed on the monitor, and listed on the printer if so selected. The presentation of the sensor- and maintenance data is shown in the example in Figure 5.16. All sensor data appear in user units if the Slave interrogation is successful. In cases of unrecoverable transmission errors, a diagnostic printout is provided for trouble shooting purposes (shown for Slave #5 in Figure 5.16).

The above brief discussion of the control software architecture and user interaction reveals the many capabilities of the Vers 2 Master station with its enhanced data analysis capabilities. It also shows the user-friendly interaction. As the software is of modular form, future commands can be added with ease. The control software is coded in the IBM-PC's interpreter Basic language, the execution speed of which is sufficient for this application. The software package outlined above does not include the remote control facility.

The photographs in Figure 5.17 and 5.18 show the Master station setup and an example of the data representation in user units on the display screen.

```
***** SCAN STARTED  DATE: 11-27-1983   TIME: 21:17   REPETITIVE SCAN  60 MIN
          TIME         ID    CHO  TILTA  TILTB   TEMP   +VB1   -VB2   +VB3   TEST
CALL  0   21:17         0  -0.04     -0     -0   -0.7   12.0  -12.1   12.0   2.46
CALL  1   21:17         1  -0.00     -0     -0   -0.9   12.1  -12.0   12.1   2.50
CALL  2   21:17         2  -0.04     -0     -0   -0.4   12.0  -12.0   12.0   2.46
CALL  3   21:18         3  -0.08     -0     -0   -0.7   11.8  -12.1   11.8   2.42
CALL  4   21:18         4  -0.04     -0     -0   -1.6   11.8  -12.0   12.0   2.46
CALL  5   21:18
          TIM CALL
          TIM CALL
          TIM CALL
          DIAGNOST -192    4.96   4.96   4.96   4.96   4.96   4.96   4.96   4.96

MAINTENANCE STATISTICS    DATE: 11-27-1983   TIME: 21:17
TIME OUT   5( 3)
PERM ERROR 5( 1)
ORIG.CALLS 0( 1) 1( 1) 2( 1) 3( 1) 4( 1) 5( 1)
```

Fig. 5.16: Format for Display of Sensor and Maintenance Data

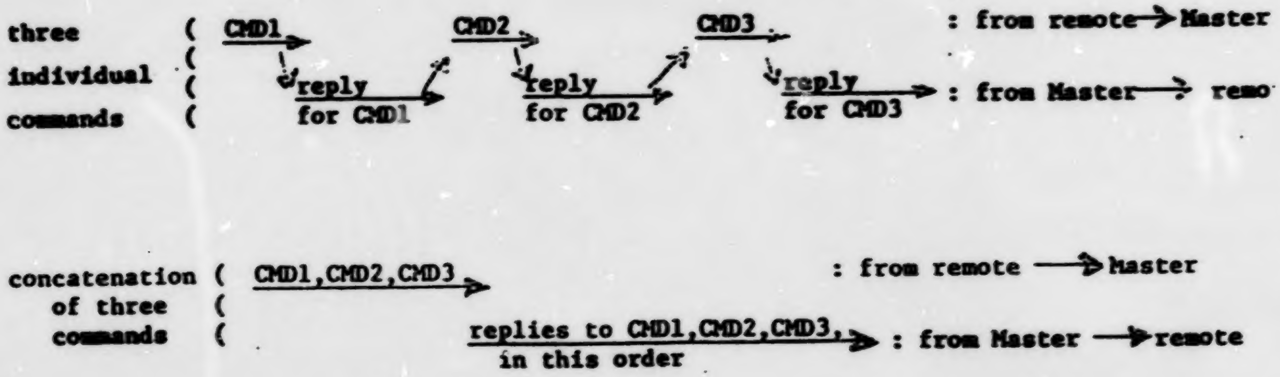


Fig. 5.19: Line Usage Optimization Using Concatenated Commands

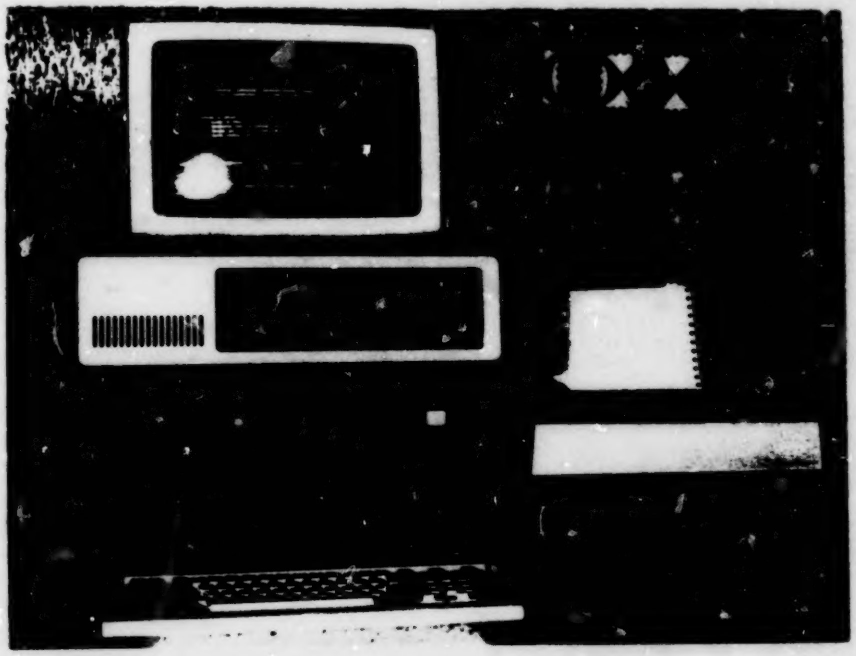


Fig. 5.17: Master Station (Vers 2)

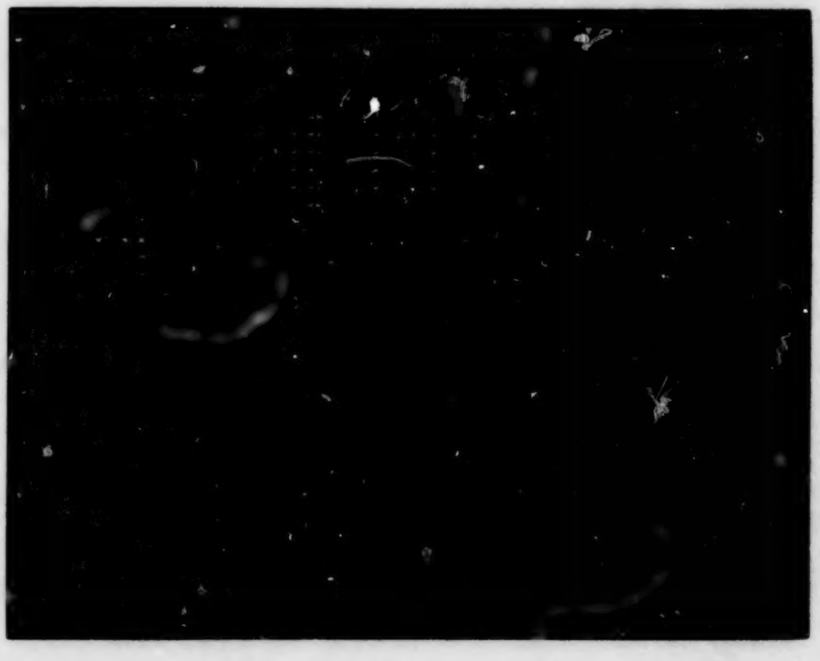


Fig. 5.18: Example of Screen Printout
(Master Vers 2)

5.6 Remote Control of the New Master

5.6.1 Objectives.

The remote control facility of the telemetry system is to permit the user to exercise the telemetry's functions from a remote location. The telemetry operation (i.e., actual interrogation of Slaves, error recovery, etc.) is to be kept entirely separate from the remote operation so that the remote end need not be concerned with the former. Command messages issued by the remote end are a simple means to provide this interface and to inform the telemetry system to perform the required functions. Reply messages sent back to the host convey return information to the remote end about successful/unsuccessful command execution and actual data from the telemetry system (i.e., sensor data, maintenance data, etc.).

The communication between the telemetry system (i.e., the Master) and the remote user is to utilize the public telephone network due to its general widespread existence and easy accessibility. Thus, ready relocatability of the remote end is provided (this also holds for the telemetry system).

The sophistication and intelligence of the remote end determines the level of the commands and replies (protocol). Two levels are envisaged and investigated. First, the user's end can be considered as a "remote console" performing exactly the functions the Master's local console will do. Second, the user's end can be represented by an "intelligent" computer which would permit higher level functions, such as automatic error recovery, automated remote command issuing and data analysis.

5.6.2 Approach and Solution

Owing to the modular architecture of the master's control software, the remote control software module can be developed separately and added to the existing software support package. The "remote console" type and the "intelligent" computer type remote control versions are contrasted.

For the "remote console" type remote end, formatting of data takes place in the Master in a manner identical to the formatting for the Master's local console. Thus, an image of the local console screen is sent to the remote user (data interleaved with explanatory text). As a consequence, this "Man-machine" line protocol uses longer reply messages and requires longer transmission periods over the public telephone network. However, this disadvantage is offset by the requirement for only a "dumb" terminal on the remote end. Automatic error recovery is abandoned in favor of error detection and recovery by the user.

In contrast, for the "intelligent" computer type remote end, a standard line protocol can be utilized (e.g., BSC, HDLC) which offers powerful inherent error recovery. Only relevant data is sent without explanatory text. Additional text is generated and inserted by the remote-end computer upon reception of the data, so as to create a user-readable display on the screen. With this "machine-machine" line protocol, data records are more compact and require less transmission time. However, this advantage is offset by the requirement for an intelligent computer terminal with user supplied software to support the first three levels of the ISO standard (physical, link end-to-end line protocols).

The superiority of one of the line protocols over the other one depends on the frequency of usage of the remote user end, and the availability (and the cost to develop) of communication support programs for the user's computer. A trade-off had to be found on the above basis.

Based on the above discussion, the "remote console" type protocol has been implemented as the expected infrequent use of the remote control link does not seem to warrant the expense that would be incurred by the implementation of the machine-machine protocol. In addition, the "remote console" type data communication can cost-effectively be carried out by utilizing the Canada-wide DataPac packet-switching network service by Trans Canada Telephone Systems through their local agents, the provincial telephone companies. International service is also available through Telecom Canada.

5.6.3 Remote Control Commands and Replies

The following basic command functions were selected for implementation on the basis of their relevance for the telemetry operation and their convenience for the user:

(a) interrogate the Master for its readiness to accept remote commands,
(b) assign a set of selected Slaves for interrogation,
(c) assign single or (automated) repetitive scan mode at a specified interval,
(d) start scan operation,
(e) set the options of the system (printer log, diskette backup, remote control),
(f) handle diskette files, transfer them to the remote user,
(g) permit sending messages back and forth between the Master and the remote end for human communication purposes between the two locations.

The above command functions copy most of the functions available at the Master's local console. A detailed list of commands and their coding is shown in Table 5.1.

In order to optimize the utilization of the public telephone line and, thus, reduce the incurred operating cost, the commands CMD can be concatenated to form a command sequence CS. Consequently, to perform a sequence of N command functions, the user needs to send only one message package rather than N individual packages. Reply messages for each of N commands per sequence are also sent as one single package from the telemetry system to the remote end. Line-turn arounds and message package charges are minimized, the line usage is optimized, thus reducing the transmission charge on public networks, particularly of the packet-switched type. Figure 5.19 shows an example of this line usage optimization concept.

The general syntax of a complete command sequence CS can be expressed as follows:

>CMD, CMD,...,CMD, CR

where > and CR (carriage return) are delimiters. Commands CMD may be separated by space(s), comma(s), or not at all. A maximum of 40 characters is allowed for the command sequence (including separators, but not including delimiters).

The reception of each command listed in Table 5.1 is acknowledged by a reply message. This message either acknowledges to the user proper reception and execution of the command, signals abnormal conditions due to transmission errors or user errors (incorrect command coding), or conveys the desired data, if any, to the remote end.

Table 5.1 Commands CMD for the Remote Control

(CR means carriage return)

CR	enquire Master status, enter remote control mode when Master ready
MS	set single scan mode
MR mmmm	set repetitive scan mode at interval mmmm minutes (mmmm = 0001 ... 1440)
CF	assign full set slave configuration
CS xxyy...zz\	assign selective set of slaves xx,yy...zz (xx,yy...,zz = 00...max. ID of slave in the system)
SD	start scan once, then send logged data
SX	start scan, then exit remote control mode immediately
SE	end scan in progress
FTd b...b e...e	transfer backup file from diskette to remote end: d=data type (S=sensor data, M=maintenance statistics, A=all of the above), b...b=starting date (MM-DD-YYYY),e...e=ending date (MM-DD-YYYY)
FDEL	delete backup file on diskette
FM x...x\	send message x...x (no commas allowed) to Master
F0	transfer current operating parameters of telemetry system to remote end
0ff	set options: ff=function (P0=printer log off, P1=printer log on, D0=diskette backup off, D1=diskette backup on)
X	exit remote control mode and return Master to manual mode

Table 5.2 Replies RPL for commands CMD

"Man-machine" line protocol Slashes (/) and quotes (') are used as separators only and are not part of the replies.

CR = carriage return, LF = line feed

Command CMD	Possible replies RPL	Condition
Any Command (common error messages)	LF/' WAITING-RETRY'/CR	if no user action detected for a period of 1 min.
	LF/' PERMANENT LINE ERROR (RCV)'/CR	if unrecoverable transmission error (remote to Master) detected or if Master cannot transmit to remote due to line or modem problem
	LF/' REMOTE CONTROL TERMINATED '/CR	if Master returns to standby mode (manual operation permitted again)
CR	LF/' WAIT'/CR	if Master not in Remote Control mode
	LF/'READY'/CR	if Master has entered Remote Control mode
MS or MR nnnn	LF/'M-DONE'/CR	if successful
	LF/'ILLEGAL'/CR	if first command character invalid
	LF/'M-INVALID'/CR	if syntax or value error(s) detected in MR
CF or CS xxyy...zz	LF'C-DONE'/CR	if successful
	LF/'ILLEGAL'/CR	if first command character invalid
	LF/'G-INVALID'/CR	if syntax or value error(s) detected in CS
SD or SE or SX	for SD: sensor and maintenance) data as shown below) followed by LF/'S-OK'CR) for SE: LF/'S-DONE'/CR) for SX: LF/'S-DONE'/CR followed) by LF/'REMOTE CONTROL) TERMINATED'/CR)	if successful
	LF/'ILLEGAL'/CR	if first command character invalid
	LF/'S-INVALID'/CR	if syntax error detected

... Continued on next page

Table 5.2 - Continued

Command CMD	Possible replies RPL	Condition
FT db...be...e or FDEL or FM or F0	for FT: searching sensor and/or maintenance data as shown below followed by LF/'F-DONE'/CR for FDEL: LF/F-DONE'/CR for FM: 'F-SONE'/CR for F0: option list as shown below followed by LF/'F-DONE'/CR	if successful
	LF/'ILLEGAL'/CR	if first command character invalid
	LF/'F-INVALID'/CR	if syntax or value error(s) detected
X	LF/'REMOTE CONTROL TERMINATED'/CR	if successful
	LF/'ILLEGAL'/CR	if command invalid

Format of sensor
data is as follows:

```
***** SCAN STARTED  DATE: 12-01-1983   TIME: 21:13   REPETITIVE SCAN  60 MIN
            TIME          ID    CH0  TILTA   TILTB    TEMP    +VB1    -VB2    +VB3   TEST
CALL  0    21:13           0  -0.04     -0      -0    -0.7    12.0   -12.1    12.1   2.50
CALL  1    21:14           1  -0.00     -0      -0    -0.8    12.1   -12.0    12.1   2.50
CALL  2    21:14           2  -0.04     -0      -0    -0.3    12.0   -12.0    12.0   2.46
CALL  3    21:14           3  -0.08     -0      -0    -0.7    11.8   -12.1    11.8   2.42
CALL  5    21:15           5  -5.00     -5      -5     4.0    12.3   -12.8    12.5   2.42
CALL  6    21:15           6   4.96      5       5     5.0    14.6   -10.4    14.4   2.46
CALL  7    21:15           7  -5.00     -5      -5     3.2    11.7   -12.1    11.4   2.34
```

Format of maintenance
data is as follows:

```
MAINTENANCE STATISTICS    DATE: 12-01-1983   TIME: 21:13
-VB2 LOW    6( 2)
ADC TEST    7( 2)
TLT A LIMT 5( 2) 6( 2) 7( 2)
TLT B LIMT 5( 2) 6( 2) 7( 2)
ORIG.CALLS 0( 1) 1( 1) 2( 1) 3( 1) 5( 1) 6( 1) 7( 1)
```

Format of option
list is as follows:

```
OPTIONS IN EFFECT:
     SLAVES IN SCAN: 0  1  2  3  5  6  7
     REPETITIVE SCAN  60 MINUTES: ACTIVE
     PRINTER LOG      ON     DISK BACKUP  ON
     REMOTE CONTROL   OFF
```

For the man-machine protocol, i.e., the "remote console" type user end, Table 5.2 contains the possible replies for all valid commands. Reply messages are cascaded to form a single package upon reception of a command sequence consisting of several commands (this achieves line usage optimization).

The remote control software module is added to the basic Master control software support as described in section 5.5. The state diagram in Figure 5.20 reveals how the remote control module interacts with the basic software, whose state diagram is shown in Figure 5.7.

5.7 Alarm Feature

The Telemetry/Monitoring System was designed as an interactive system where interrogations of slave stations are initiated by the central Master station. This "reporting-on-demand" operation does not require the slave stations to be active all the time, and represents one of the key features leading to a 1-year operation lifetime under battery power. The widely variable interrogation rate also lends itself to trend analysis where the rate is increased only when significant changes in the logged sensor data are detected by the Master.

Contrasting these important advantages is the disadvantage that a sudden change in the sensor data is not detectable until the next scheduled interrogation, resulting in an "uncertainty" interval. For the normal intervals of 24 hours between interrogations, as used for the Sparwood project, this "uncertainty" of 24 hours is too long in order to use the sensor readings for alarm purposes in cases of unexpected earth movement.

At the present time, the only way to decrease this "uncertainty" interval to, e.g., 6 hours, is to increase the interrogation rate of all

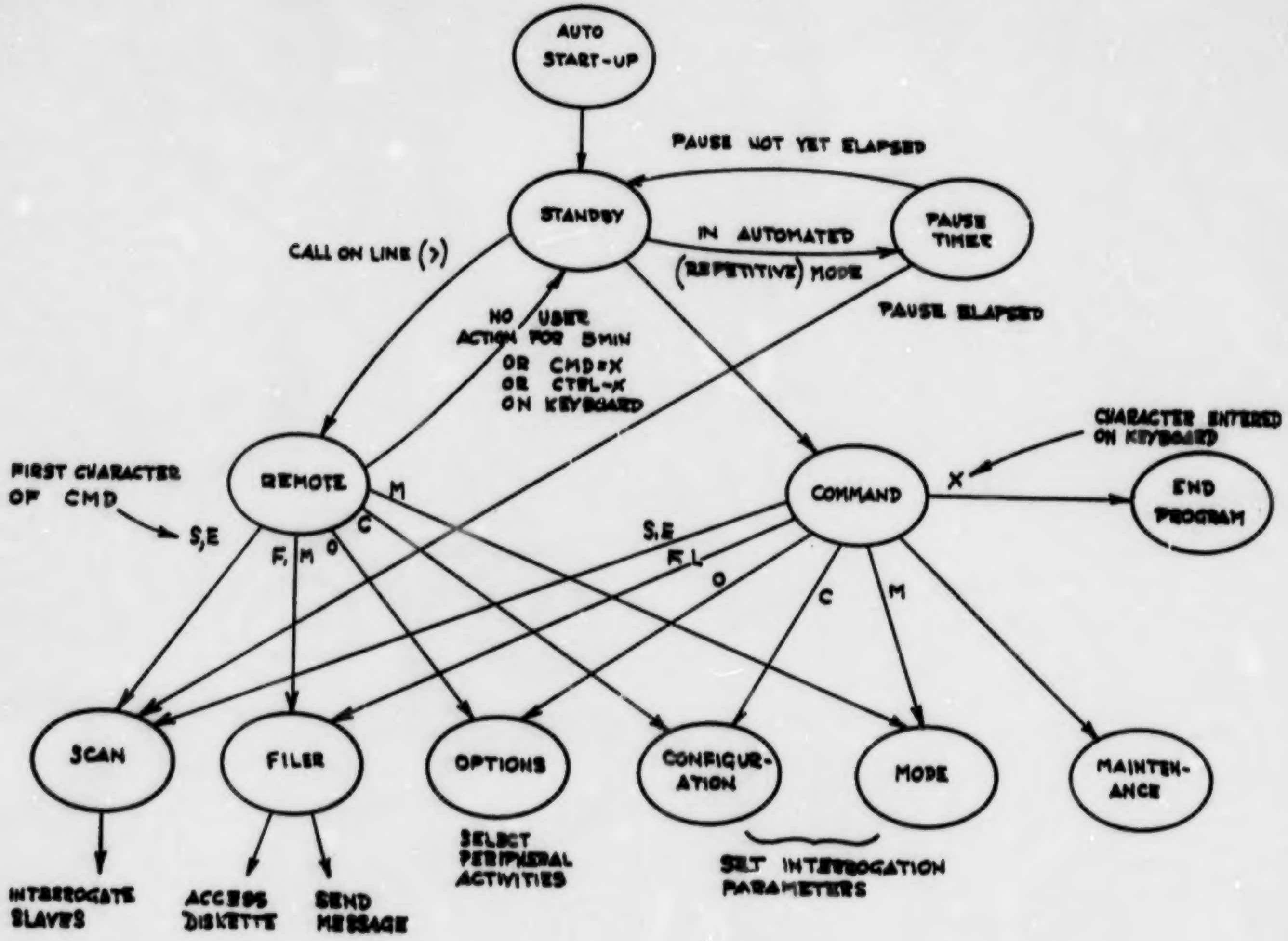


Fig. 5.20: State Diagram of Master Operation with Remote Control

slaves to 4 interrogations per day. This, however, leads to increased battery drain and shorter life expectancy of the slaves' batteries.

An alternative solution is an alarm feature which is researched and outlined in this chapter.

5.7.1 Objectives

An alarm feature is researched which is internal to each slave station and which reduces the above "uncertainty" period. Without Master intervention, each slave automatically tests the sensor data at pre-specified intervals, e.g., 6 hours, and alarms the Master only if abnormal sensor readings are detected. Because this internal data logging and testing session does not require the battery-draining data transmission via VHF and is of shorter duration than regular interrogations via the Master, the required battery energy consumption per slave is less than for regular interrogations by the Master. Consequently, more daily alarm sessions can take place without reducing the battery lifetime. As the regular interrogation intervals via the Master can even be done at longer intervals (since no sudden changes are lost), an overall savings of battery power consumption can be achieved.

5.7.2 Principles of Operation

The alarm feature and the interrogation via the Master are independent of one another. Only a Slave station which detects an "alarming" change in its sensor readings alerts the Master of this condition at once. The Master than interrogates the Slave to log the alarming data, and resets the condition(s) of the alarm.

In order to equip the current telemetry system with the alarm feature, some minor hardware and software changes are necessary which are discussed in the next section. The sequence of activities in Slave and Master stations can best be described by a flow diagram as illustrated in Figure 5.21.

A hardware timer initiates normal data logging at user selectable intervals (6 min...24 hrs) via the ALRT-M signal. The Slave's MPCU and DACM modules power up to take the sensor readings. The readings are compared against a pair of upper and lower thresholds. If within this range, no action is taken, and the Slave returns to stand-by mode immediately. If exceeding any one of the thresholds, an alert tone ALRT-S (1600 Hz) is sent to the Master signalling this event. Then the Slave returns to the stand-by mode. The energy requirement for this short (7...9 sec) alarm testing is less than that for regular interrogation because of the shorter duration (no waiting time or time-out) and because no transmission takes place in most cases. This saves energy of the critical telemetry battery (VB3).

In order to make the alarming of the Master insensitive to possibly ongoing normal interrogations which otherwise might cause a loss of the alarm call, no further identification data about the alarming slave is sent. Instead, the Master interrogates all Slave stations in the system (full scan). However, by way of a new data request command 'A' only that Slave which caused the alarm sends the data. This saves on battery energy in all other slave stations. In order to avoid further alarms based on the current alarming condition, the Master either disables the alarm function of the alarming Slave or sets thresholds of the latter higher via command. The user may be alerted about the existence of an alarm condition in some

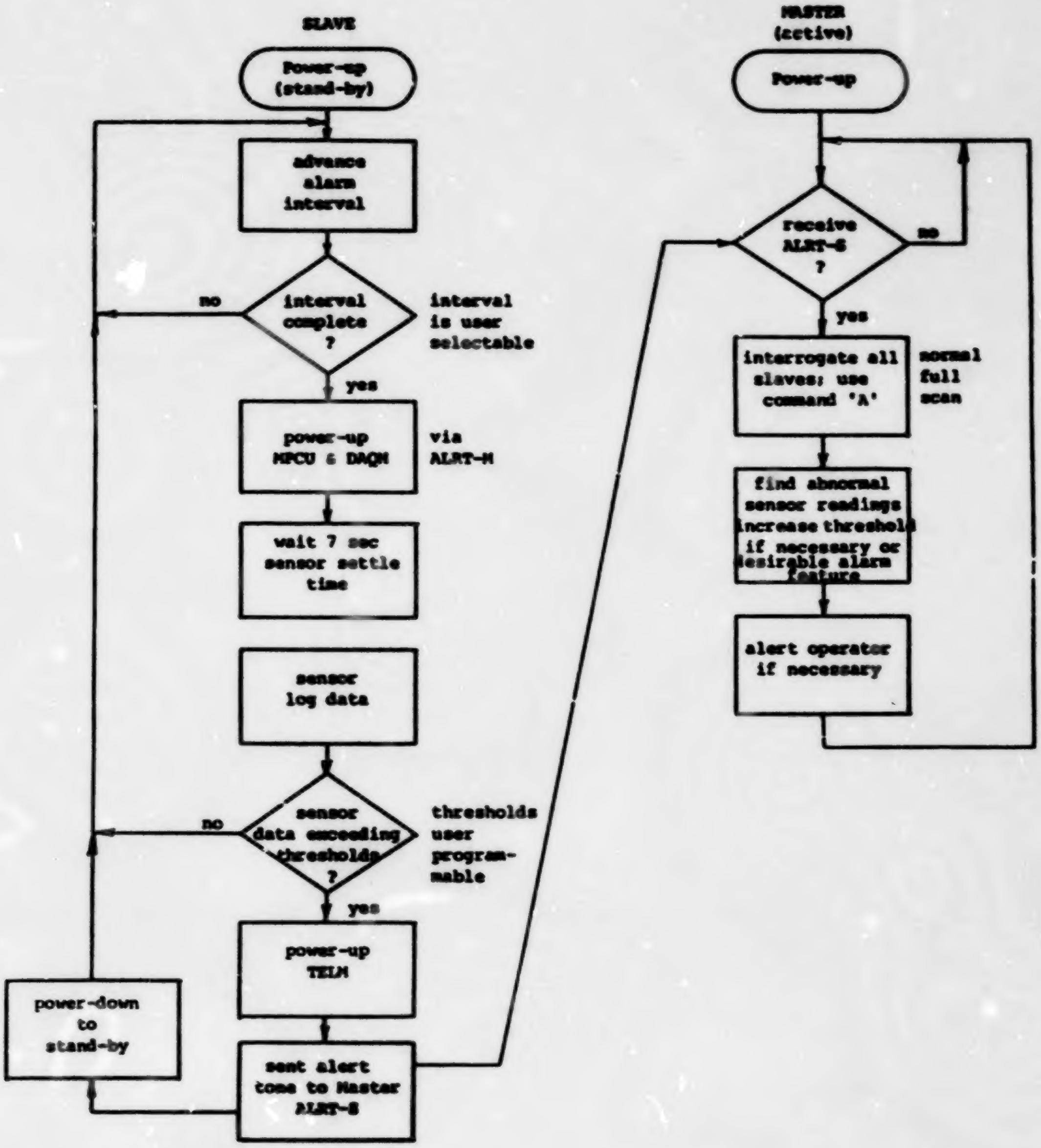

SLAVE
Power-up (stand-by)
advance alarm interval
no
interval complete ?
interval is user selectable
yes
power-up MPCU & DAQM
via ALRT-M
wait 7 sec sensor settle time
sensor log data
no
sensor data exceeding thresholds ?
thresholds user programmable
yes
power-up TELM
power-down to stand-by
sent alert tone to Master ALRT-S
MASTER (active)
Power-up
receive ALRT-S ?
no
yes
interrogate all slaves; use command 'A'
normal full scan
find abnormal sensor readings increase threshold if necessary or desirable alarm feature
alert operator if necessary

Fig. 5.21: Flow Chart for Slave-Master Interaction Using the Alarm Feature

way, possibly via the built-in public telephone connection, if available.

The Slave's alarm interval is restarted upon every normal interrogation by the Master to avoid shorter than necessary tests for alarm conditions.

5.7.3 Hardware Support of the Alarm Feature

The block diagram in Figure 5.22 illustrates the necessary hardware additions. The timer is an add-on module using CMOS devices for low power drain. The ALRM signal is generated at intervals that can be selected by the user when the Slave is installed. The hardware changes in the existing slave units comprise an added ALRT-S tone generator (1600 Hz), an output port to control the timer operation under command control and a non-volatile memory (RAM), which retains the alarm parameters (thresholds) when the slave is powered up.

The expected additional power drain for the stand-by power off VB3 is less than 1mA at 12V nominal. Thus, no significant load is added to the telemetry battery B3.

5.7.4 Software Support of the Alarm Feature

The Slave's control software must distinguish between normal interrogations and the alarm function (via ALRM) and carry out the proper operation as shown in Figure 5.21 for the latter case. No new action need be included in the existing remote's control software, except for the threshold testing and the generation of the ALRT-S tone.

For additional flexibility of the alarm feature, it is recommended to include four new commands in the Master/Slave communication:

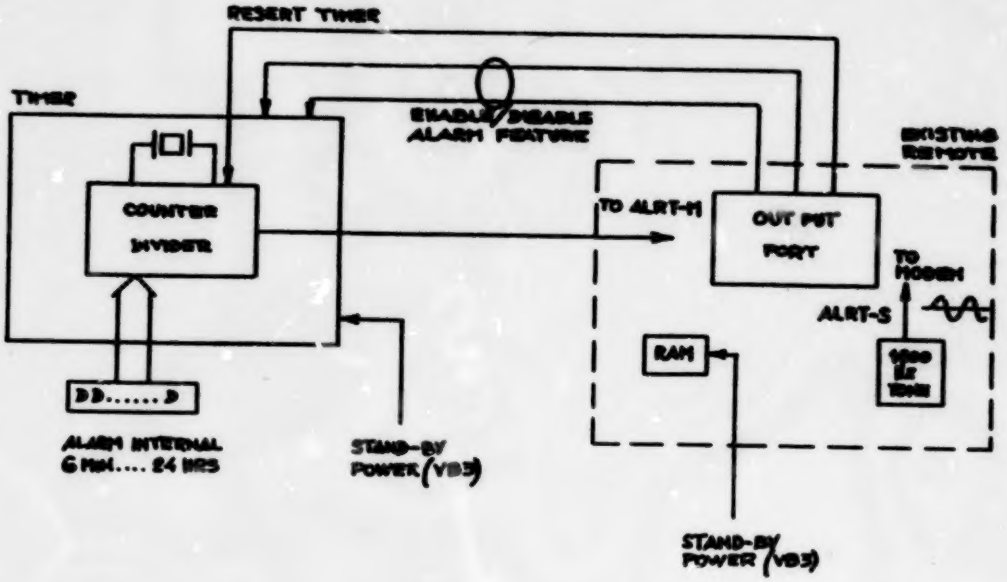


Fig. 5.22: Blockdiagram of the Hardware Support for the Alarm Feature

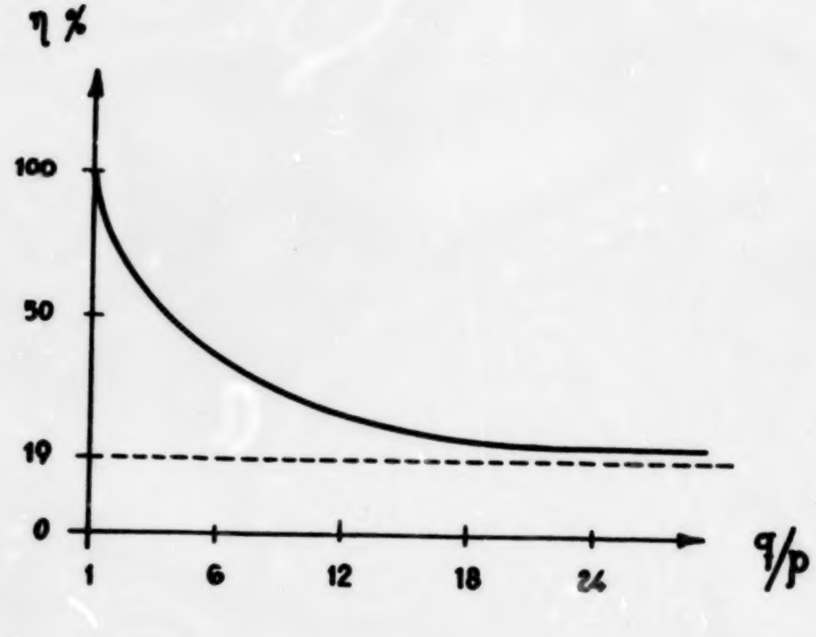


Fig. 5.23: Estimated Reduction of Battery Consumption Using the Alarm Feature

D	normal data request	existing
R	retransmission request	
A	data request if in alarm mode (remote sends data only if it has detected a previous alarming condition)	
X	turn alarm feature off	
Y	turn alarm feature on	
T llluuu	set lower and upper thresholds (-5...+5V).	

The command A ensures that only those Slaves respond to a full scan interrogation which detected an alarming condition previously and did cause the alarm. No other Slaves need reply. By means of commands X and Y the alarm feature can be turned on or off in each Slave individually. The T command allows the programming of the upper and lower alarm thresholds when the sensor data gradually (and normally) changes.

The new set of commands allows the Master to exercise full control over the alarm feature of each slave station.

5.7.5 Battery Savings

The justification of the alarm feature is based on a possible increased sensor data testing rate at a constant or even decreased Slave's battery consumption. This effect is analysed here.

Assume a telemetry system with:

N remote stations

p full scans per day (interrogation via Master)

q alarm tests per day (automatically done by Slave).

The energy consumption in terms of the ratio q/p at constant (but arbitrary) "uncertainty" intervals can be expressed in a normalized manner as:

$$\eta = \frac{74.4 + q/p \cdot 14.4}{q/p \cdot 74.4} \quad 100\%$$

where η is shown graphically in Figure 5.23.

For no alarm test, i.e., $q/p=1$, the normalized consumption is 100%. The more internal alarm tests are performed between two regular interrogation intervals by the Master, the more reduction in battery consumption is achieved. Only approximately 19% of battery consumption is needed, for instance, if during a full year only alarm tests are being performed and only one regular interrogation takes place. Although this is an extreme case, the savings accorded to the use of the alarm feature are clearly seen.

A realistic example related to the Sparwood subsidence monitoring project will show the possible savings of battery energy in practice. Assume a 1-year operation with $N=10$ slave stations operated at 4 full scans a day and no alarm feature in use. A total battery energy consumption of 30.2 Ah per slave station is the result. Then assume the use of the alarm feature with 4 alarm tests per day and 1 full scan per day. The resulting battery energy consumption is 11.9 Ah. Thus a savings of 60.5% on the battery consumption is achieved for the same "uncertainty" period of 1/4 day = 6 hours. This savings for the above conservative example justifies the future incorporation of the alarm feature into the current telemetry/monitor system.

6. RESEARCH DEALING WITH THE PREDICTION OF MINING SUBSIDENCE

6.1 Review and Classification of the Prediction Methods

Due to a limited budget assigned to this part of the contract, the consultants limited the research to:

(1) General review and classification of the prediction methods.

(2) Empirical modelling and evaluation of the subsidence in the test area.

(3) Preliminary study on the use of the finite element method in the test area.

(4) Geometrical analysis of deformation surveys.

Generally, the following two basic methods may be distinguished in the analysis of deformations of any deformable body:

(1) Geometrical analysis which is supposed to give information on the geometrical status of the deformable body, the change of its shape and dimensions; and

(2) Physical interpretation which gives information on the physical status of the deformable body, the state of internal stresses and the relationship between the loads (causative effects) and deformations, which is utilized in the development of prediction theories.

From the point of view of time dependency, the deformation analysis may be classified as either static or dynamic. In static analysis, the load is treated as constant and the response (the deformation) is treated either as a final response at the given instant of time, or as time dependent (e.g., creep of material or settlement of a structure) in which the information on the rate of deformation is of interest. Dynamic analysis is performed when the loading (causative effects) and response are changeable with time, and it is of interest to find the frequency and amplitude of the changes. If the load changes are slow, then repeated deformation surveys may be used either for a static analysis of the deformation at a certain instant of time, or for a dynamic analysis.

In the case of geometrical analysis, the information on the acting forces and stresses and mechanical properties of the body are of no interest to the interpreter or are unknown. As a final result of the geometrical analysis, usually only relative displacements of discrete points and their variance-covariance matrix are derived from the given repeated observations and compared with given tolerances for the deformations. In a more refined analysis, the relative displacements are analysed for a deformation trend and the displacement field is approximated through a least-squares fitting of a deformation model. The displacement field may be readily transformed into a strain field which describes in a unique way the geometrical status of the deformable body (Chrzanowski et al., 1983).

In the case of physical interpretation, the information on the load-deformation relationship may be obtained by using either an empirical method through a correlation of observed deformations with the observed loads (external and internal causes producing the deformation), or a deterministic method which utilizes information on the loads, properties of the material, and physical laws governing the stress-strain relationship. The two methods, deterministic and empirical, may be combined together for the purpose of physical interpretation.

Sophisticated numerical procedures, such as the finite element method, which have become more and more frequently used in deterministic modelling of the relationship between loading, material properties and deformation, allow for a more meaningful comparison between the predicted (designed) and observed deformations. This also influences the design of an observation scheme, especially with regard to instrumentation and its location and with regard to the heightening of accuracy requirements.

Due to many uncertainties in the deterministic method of deformations, the theoretically calculated displacements $\underline{\delta}_t$ (or any other deformation quantities) will generally depart from the observed values $\underline{d}$.

The discrepancies may be due to the approximations of the deterministic method or due to:

— imperfect knowledge of the material properties, for example, errors in the elasticity constants;

— wrong modelling of the behaviour (elastic instead of plastic or creep neglected, etc.) of the material;

— errors in the thermal parameters of the material;

— measuring errors of the empirical method;

— measuring errors in sampling and incomplete sampling of loading (causative) effects.

The investigation of the discrepancies is useful in gaining a better knowledge of the behaviour of the deformable body. Statistical tests on the discrepancies (Chrzanowski et al., 1982) may help in finding their nature and source. If the discrepancies Δ are tested to be of a systematic nature then the deterministic and empirical methods are combined for the interpretation of the deformation measurements. One way of doing this is to assume that the systematic discrepancies are caused, for example, only by the improperly chosen material parameters, say E and ν. In this case, new ("calibrated") values of the parameters are estimated by applying the least-squares criterion:

$$\min_{E,\nu} \{(\underline{\delta}_t-\underline{d})^T C_\Delta^{-1}(\delta_t-d)\} \qquad (15)$$

where C_Δ is a variance-covariance matrix of Δ.

This method for the calibration of the constants of the deterministic model may lead to physically unacceptable values of the calibrated quantities if the real reason for the discrepancy is of a different source. In such a case, one has to try another approach.

The empirical models of deformations deal usually with small deformation quantities which are at the margin of measuring errors. Therefore, a very careful accuracy analysis and statistical testing of the results are required in order to make proper decisions on the acceptance of the deformation model.

In order to develop a meaningful theory for predicting ground subsidence in mining areas, one has to go through the above outlined analysis and comparison of the deterministic and empirical modelling of the deformation.

Figure 6.1 shows a flowchart (Chrzanowski and Hart, 1982) of operations involved in the control of mining subsidence and in the development of the prediction theories which require the following steps:

(1) Preparation of maps, cross-sections and profiles of the surface topography, geology, tectonics, and mining operations.

(2) Design of the deformation surveys on a basis of expected (predicted) deformations.

(3) Data acquisition (repeated surveys) and the accuracy evaluation.

(4) Calculation of displcements $\underline{d}$ and their accuracies.

(5) Geometric analysis (fitting a deformation model) and evaluation of the deformation parameters.

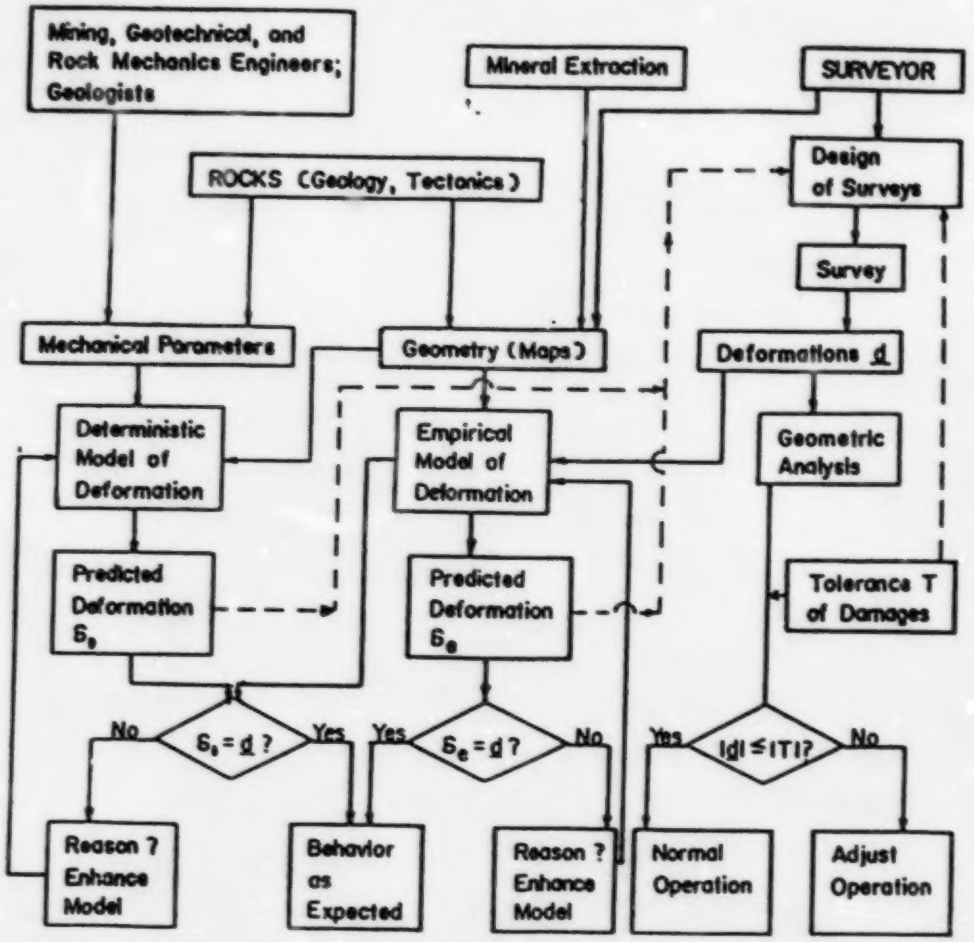

Mining, Geotechnical, and Rock Mechanics Engineers; Geologists
Mineral Extraction
SURVEYOR
ROCKS (Geology, Tectonics)
Design of Surveys
Survey
Mechanical Parameters
Geometry (Maps)
Deformations $\underline{d}$
Deterministic Model of Deformation
Empirical Model of Deformation
Geometric Analysis
Predicted Deformation δ_t
Predicted Deformation δ_e
Tolerance T of Damages
No
$\delta_t = \underline{d}$?
Yes
Yes
$\delta_e = \underline{d}$?
No
Yes
$|\underline{d}| \leq |T|$?
No
Reason ? Enhance Model
Behavior as Expected
Reason ? Enhance Model
Normal Operation
Adjust Operation

Fig. 6.1 Flowchart of Operations in the Analysis and Prediction of Mining Subsidence.

(6) Comparison of the observed deformations $\underline{d}$ with the given tolerances for the damages. If statistically $|\underline{d}| > T$, then advice is given to the mining authorities on prescriptive measures (adjustment of operation) to be taken.

(7) Correlation of observed deformations $\underline{d}$ with the geometry of the extraction area and with the geology of the overburden and the development of the empirical model of the deformation for predictions.

(8) Calculation of predicted deformations $\underline{\delta}_e$ for future extractions.

(9) Statistical comparison of the predicted deformations with the observed values $\underline{d}$. If, statistically, $\underline{\delta}_e \neq \underline{d}$, the empirical model is corrected.

(10) Comparison of the empirical model with the deterministic model. If statistically $\underline{\delta}_t \neq \underline{d}$, then the surveyor's data is used to correct the deterministic model.

Thus the control of strata movement and the development of the prediction theories is a very complex task which has generally been underestimated in the Canadian mining industry. The subsidence analysis and prediction require a close cooperation between mining, geotechnical and rock mechanics engineers, geologists and survey engineers who must have a good understanding of both the empirical and deterministic (mechanistic) modelling of the deformations.

The need for control of mining subsidence has long been recognized in Europe where minerals have been extracted under densely populated areas. The first attempts to investigate and analyse the mechanism associated with mining subsidence were initiated in Belgium as a result of mining subsidence and structural damage suffered by the City of Liege in the 1820s. Gonot's treatise (Kratzsch, 1983) is the most notable achievement of that era. Since that time many theories for predicting the behaviour of rock masses over underground mining have been developed in Europe.

As aforementioned, all the theories may be classified into two basic types: i) those based on deterministic modelling of the subsidence and ii) those based on empirical (statistical) models obtained through fitting of displacement functions into observed deformations. A good review of the theories is given by Kratzsch (1983). Most of the theories have been developed on the basis of the empirical data gathered from many years of subsidence monitoring.

One of the more popular empirical theories (Budryk-Knothe's theory) was described in the previous Final Report and it was used by the consultants in the preliminary prediction of the subsidence over the sub-panel 06-100 in Sparwood (see section 6.2 below).

One should be aware that the empirical data collected in Europe is good for a development of prediction theories only for the similar conditions in which the survey data was collected. In North America there is not available sufficient survey data on mining subsidence which would be suitable for a development of our own empirical prediction theories. Therefore it seems logical that we should try in our research to take advantage of the modern computer technology and apply numerical methods in the development of the prediction methods using deterministic modelling. Particularly, the finite element method despite some aforementioned weaknesses and despite its complexity should be put into more use in the Canadian mining industry.

In this report the consultants give (see section 6.3 below) an example of the use of the finite element method in analysing and predicting the subsidence in the test area in Sparwood and compare the results with the observed data.

6.2 Empirical Modelling Using Budryk-Knothe Theory

Most of the empirical theories dealing with the prediction of the mining subsidence are based on the so-called influence functions which describe a functional relationship between certain empirical parameters and the expected subsidence at selected points. Examples of frequently used empirical parameters are: limiting angle β of influence (angle from the horizontal at the edge of the extracted area to a point on the surface where the subsidence is negligibly small), critical radius r of the extracted area which produces the maximum subsidence, bulking coefficient of the caved in rocks in the extracted area, etc. The shape of the influence function is usually also determined empirically from the actual subsidence surveys or on a basis of certain assumptions such as, for example, that the volume of the subsidence trough on the surface must be smaller than the volume of the extracted area.

The Budryk's and Knothe's theory is one of the easiest to apply in practice and, therefore, it has been selected by the consultants to predict the subsidence in the study area over the sub-panel 06-100 (Fig. 6.2). A detailed outline of the Budryk-Knothe theory was given in the 1980 Final Report. The theory was developed for the coal district in Upper Silesia in Poland.

The theory is based on the influence function:

$$W(x,y) = \frac{W_{max}}{r^2} \iint_S \exp\left[-\frac{\pi}{r^2}(x^2 + y^2)\right] ds$$

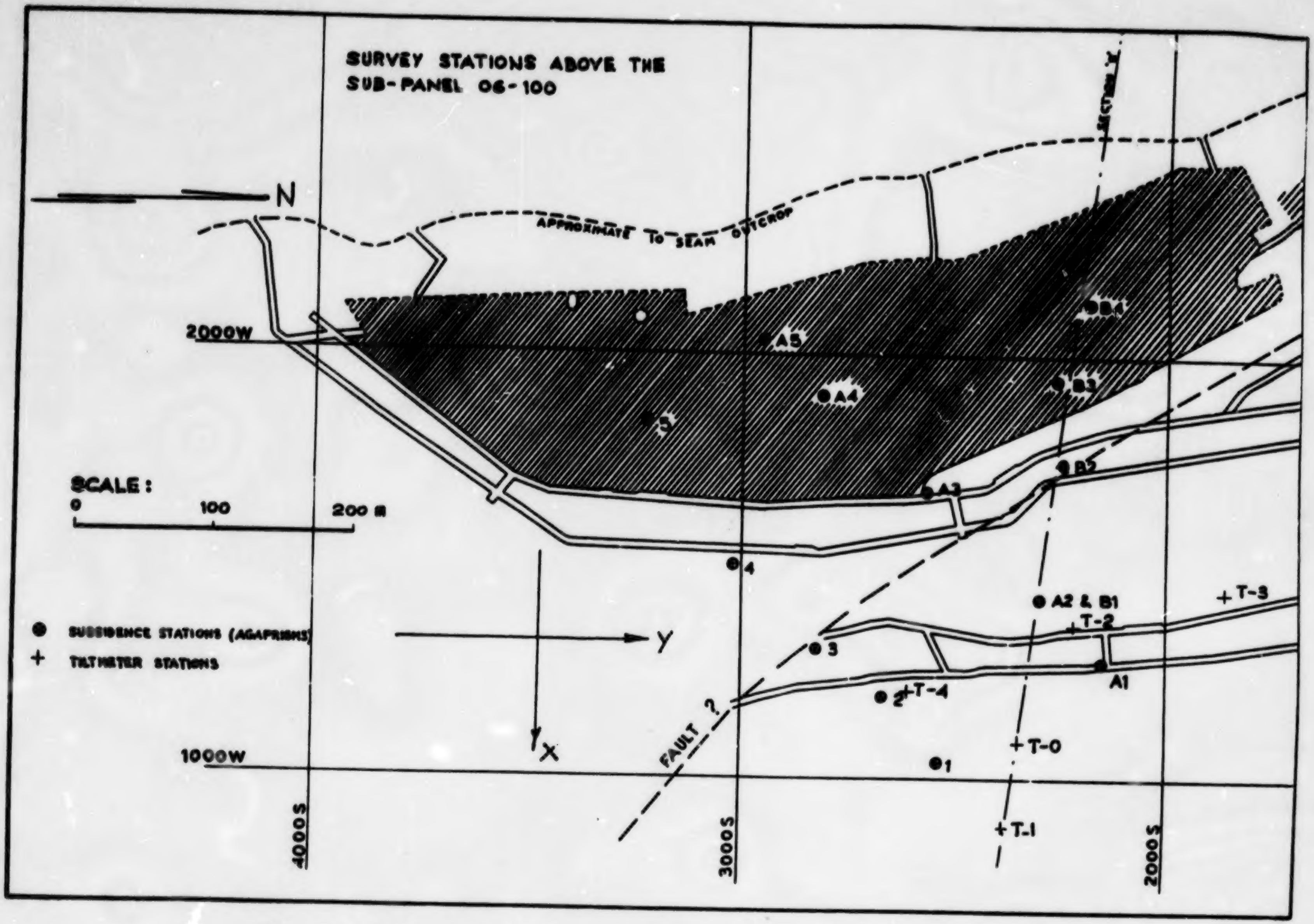


Fig. 6.2 Survey Stations above the Sub-panel 06-100.

where:

$W(x,y)$ is predicted subsidence at a point (x,y)

W_{max} = $a \cdot g$ where g is the thickness of the extracted mineral and "a" is the empirical bulking coefficient

r = H cot β, where H is depth of the exploitation, and β is the empirical limiting angle to a point at which the final subsidence may reach 1.22% W_{max} if the exploited area S is equal to or larger than the critical area.

For the Polish coal district the angle β may vary from about 30° for very strong strata to over 60° for very broken strata.

Since no information on the angle β in the Sparwood area was available, the Consultants performed their analysis for two values: $\beta_1=40^\circ$ and $\beta_2=60^\circ$. The Budryk-Knothe theory applies to horizontal or slightly inclined (up to 15°) extraction areas. In the case of the steeply inclined sub-panel 06-100 the method had to be modified by the Consultants by shifting all the subsidence parameters (point of W_{max}, limiting angle, point of maximum strain, etc.) by an empirical value of 0.7α (see 1980 Final Report), where α is the dip angle. The Budryk-Knothe theory has been applied in a graphical mode (segments of equal influence drawn on tracing paper at the scale of the mining map) as explained in the 1980 Final Report.

Fig. 6.3 shows a vertical cross-section of the extraction area (section B in Fig. 6-2) and summarizes the results of the analysis for the two alternative limiting angles $\beta_1=40^\circ$ and $\beta^2=60^\circ$ with an average H=200 m, angle of dip $\alpha=35^\circ$, g=12 m and a=0.75.

The results predict that the maximum subsidence could reach the value of 3.15 m and 7.50 m for $\beta_1=40^\circ$ and $\beta_2=60^\circ$ respectively. The 1.22%

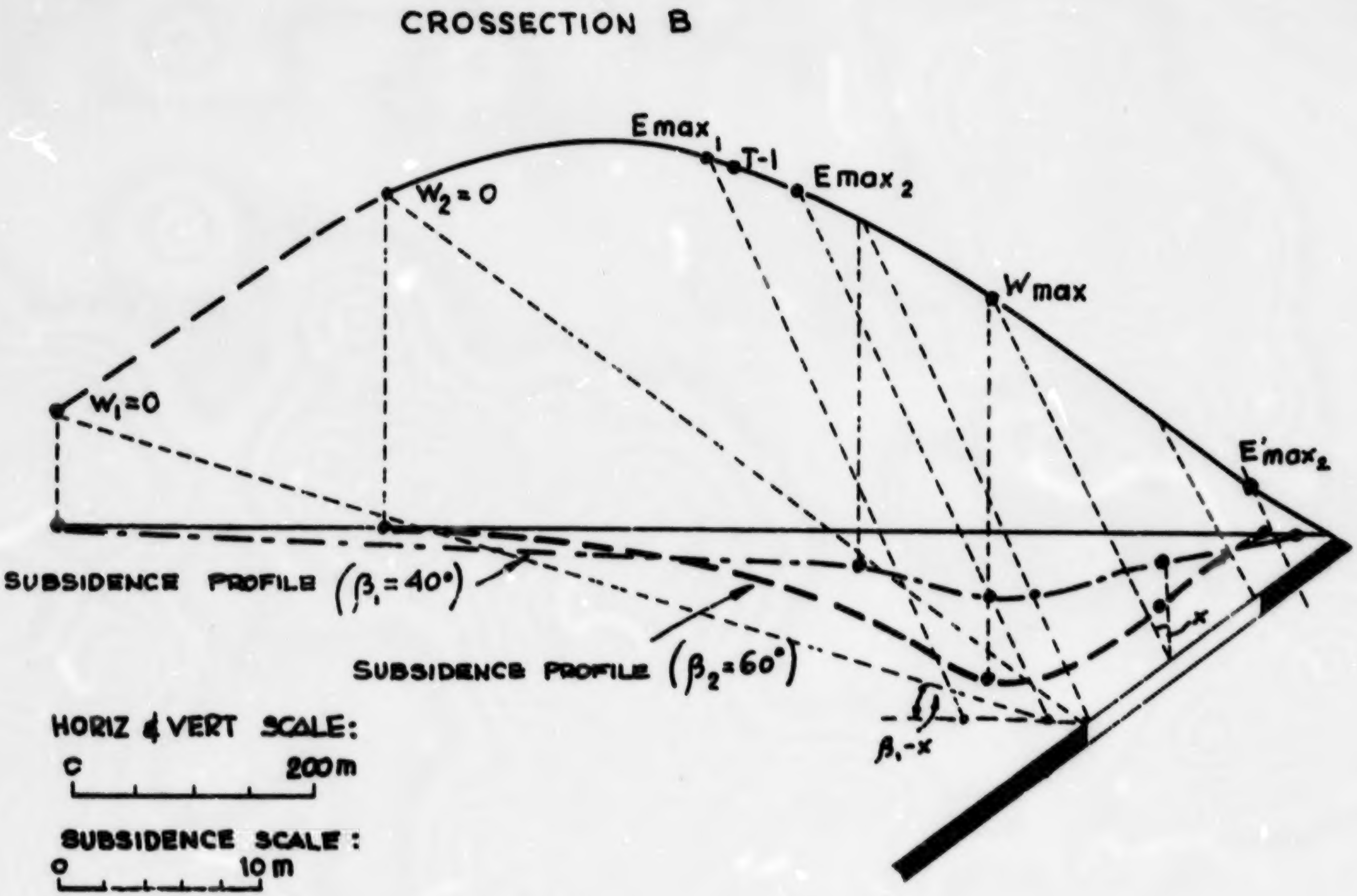


Fig. 6.3 Predicted Subsidence Profiles using Budryk - Knothe's Theory.

W_{max} (shown as W=0) subsidence could reach the surface far beyond the ridge with possible fracture zones in the vicinity of the points at which maximum strains E_{max} could develop. In the case of the sub-panel 06-100, the maximum strains could reach the values: E_{max1}=8 mm/m and E_{max2} = 39 mm/m, which could cause fracturing of the surface.

When comparing the predicted values with the actually observed displacements (listed in Table 6.1) at the points shown in Fig. 6.2, one can see that the alternative with $\beta=40^{\circ}$ gives a better agreement because the maximum subsidence (station B-4) has reached -2.18 m with a total vector of displacement equal to: 3.00 m.

In 1982, fractures on the surface were noticed in good agreement with the predicted zone between E_{max1} and E_{max2} (Fig.6.3).

Thus, in general terms, the Budryk-Knothe theory could be used for an approximate estimation of the subsidence parameters, particularly if a better knowledge of β would be available. However, as already mentioned earlier, the empirical methods if transferred to a new area may lead to large disagreements and can never be fully trusted. In the case of the sub-panel 06-100, where a fault plane is suspected as shown in Fig.6.3, the empirical theory may fail completely and the obtained reasonable agreement could be just coincidental. Besides, the results obtained from the applied prediction theory do not account at all for the actually observed large horizontal displacements of points (Table 6.1) which are very important in the interpretation of the mechanics of the subsidence. Therefore, the Consultants put great emphasis on the use of the deterministic rather than the empirical modelling of subsidence as shown below.

6.3 Use of the Finite Element Method in Deterministic Modelling of Strata Movement at the Sparwod Test Site

A 2-D Finite Element analysis has been applied for the crossection "B" as marked on the Fig. 6.2. Rectangular and quadriangular finite elements have been used in the analysis as shown in Fig. 6.4.

Since the time allocated in the contract to the research on the prediction of mining subsidence was quite small, most of the work, including the development of the FEM programme has been done beyond the scope of this contract. However, the Consultants feel that due to very encouraging results obtained in this research, at least a brief summary of these results should be given in this report.

The 2-D FEMMA (Finite Element Method in Mining Applications) programme was developed by Mrs. A. Szostak-Chrzanowski, who voluntarily gave numerous hours of her time in utilizing her programme for our research.

The computer programme is very universal, allowing to calculate displacements, strains and stresses in every element for the given material properties as well as for the given boundary conditions and body forces.

In order to inrease the accuracy of the FEM solution when using quadriangular elements of irregular shape, a six point integration technique is utilized in the FEMMA programme. The programme allows also for modelling of heat transfer and thermal strains (e.g., in analysing underground fires). In case of elastic-plastic deformations and of geological or tectonic discontinuities (for instance geological faulting) an iterative method is applied by changing the modules of elastiity in those elements whih are suspected of being in the plastic or discontinuity zones.

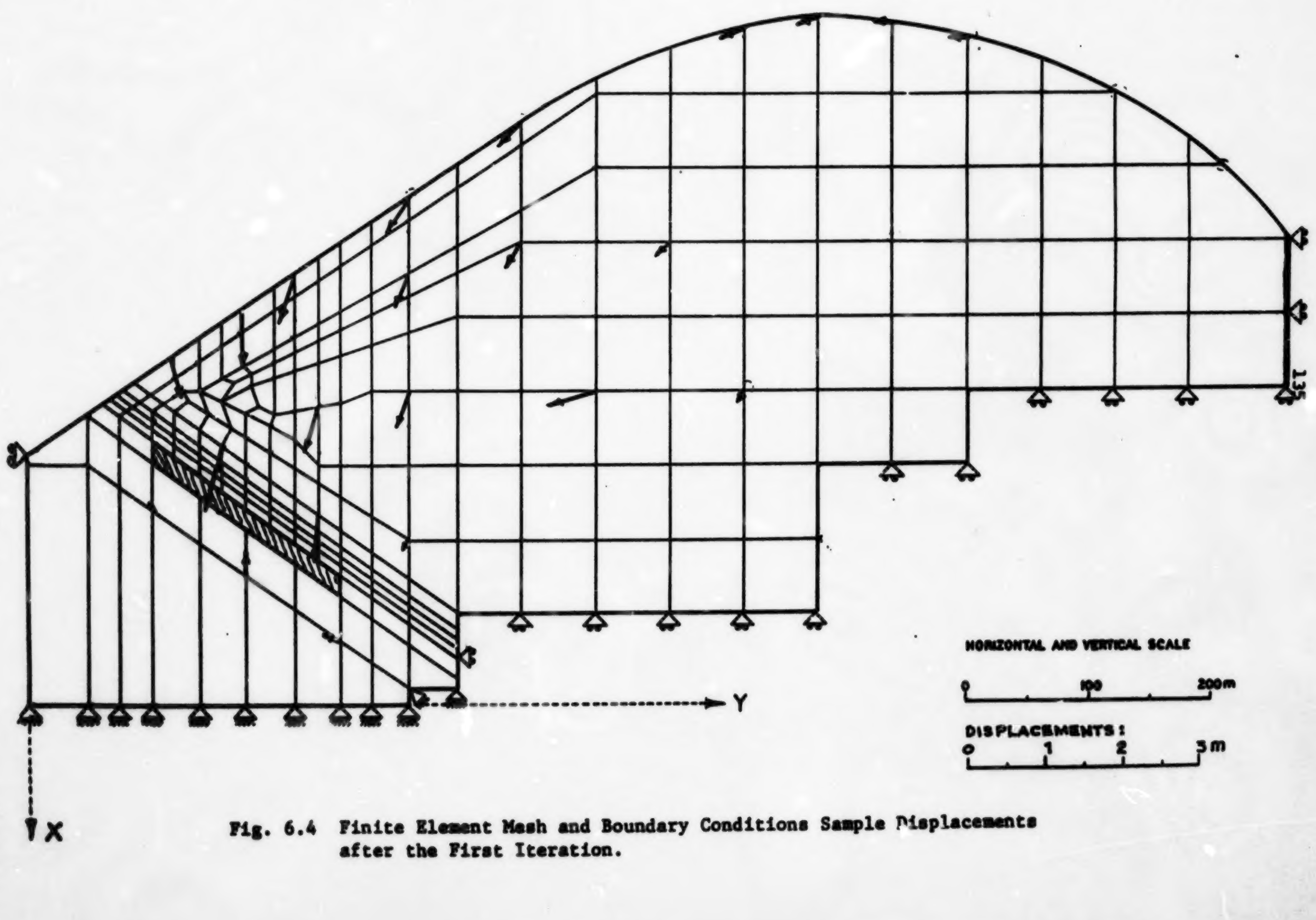


Fig. 6.4 Finite Element Mesh and Boundary Conditions Sample Displacements after the First Iteration.

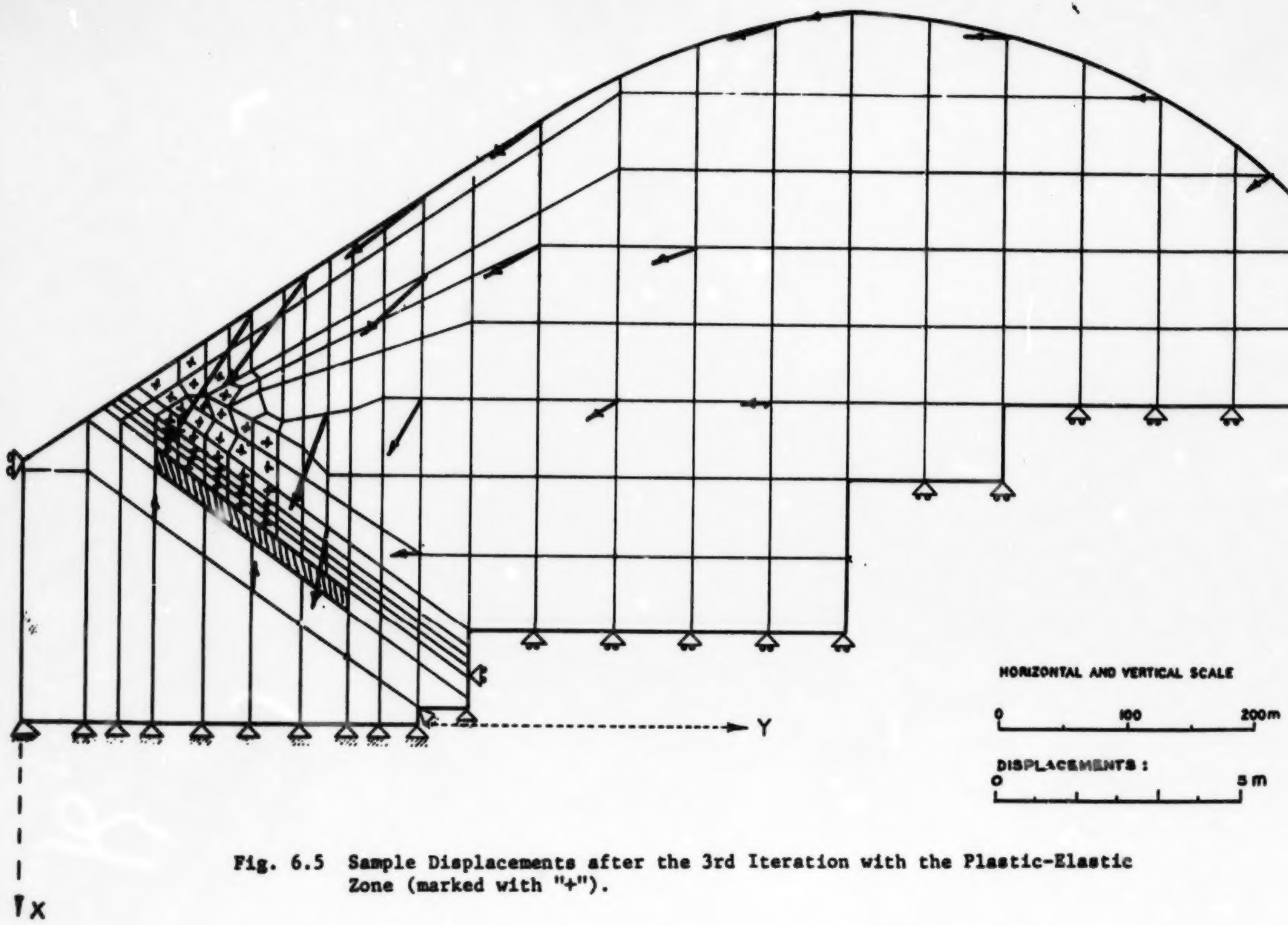


Fig. 6.5 Sample Displacements after the 3rd Iteration with the Plastic-Elastic Zone (marked with "+").

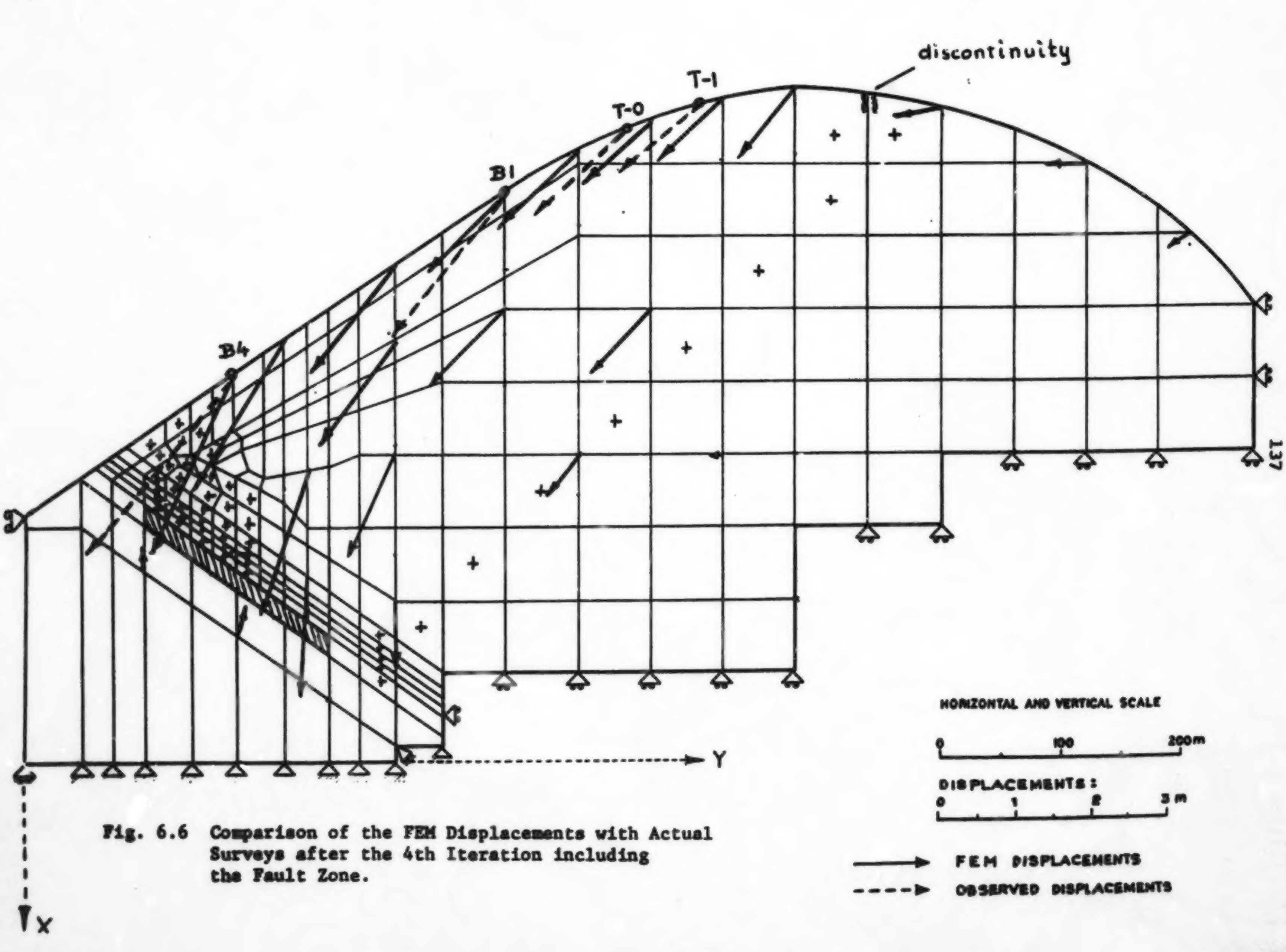


Fig. 6.6 Comparison of the FEM Displacements with Actual Surveys after the 4th Iteration including the Fault Zone.

Fig. 6.4 shows the boundary conditions applied in the analysed crossection which constrain the displacements of some nodal points, which are assumed to be beyond the influence of the marked extraction of sub-panel 06-100.

The only geological information which has been available for this analysis was that the strata above sub-panel 06-100 consists of medium strong sandstone and shale. There was also some information about a suspected fault as marked in the Fig. 6.2 with a possible surface trace near the top of the ridge. With this very limited information, the following parameters were acepted for the first iterative solution in which the rock material has been treated as a homogeneous and elastic material with a module of elasticity $E = 10^6$ kN/m^2, Poisson ratio $\nu = 0.3$ and the specific weight $\gamma = 27$ kN/m^3. Fig. 6.4 shows a few sample displacements obtained from the first iteration. Fig. 6.5 shows results of a third iteration in which those elements which demonstrated a critical change from the compressive to tensional stresses (marked with "+") have been treated as plastic-elastic with $E = 10^3$ kN/m^3. The final iteration (Fig. 6.6) included the suspected fault in form of a decreased elasticity ($E = 10^3$ kN/m^2) in those elements through which the fault line was drawn. Normally, one or two more iterations should have been made in order to reduce the influene of those elements which would still exhibit critial tensional stresses. However, due to the limited time, the results of displacements in Fig. 6.6 have been accepted as the final ones and compared with the observed displacements (supplied by the Survey Office of Westar Mining) at the surface stations T-1, T-0, B-1 and B-4. The agreement is astonishingly good taking under consideration the very limited geological information available to the Consultants. The example is a perfect demonstration of the potential of the FEM in the analysis of mining subsidence. The method could certainly be applied to the strata control above the planned extraction of the sub-panel 06-200.

6.4 Geometrical Analysis of the Observed Deformations

Results of monitoring surveys, whether obtained from terrestrial geodetic surveys or aerial photogrammetry surveys, usually are presented in a form of displacements (changes in coordinates) at discrete points. A direct use of the displacements in any subsequent interpretation of the mechanism of the deformation is rather difficult or impossible. One is interested in a global deformation picture in the subsidence area and in such deformation parameters which describe the deformation in a unique and continuous way. In a 3-D analysis in an x, y, z coordinate system, the deformation of a deformable object is fully described if the following parameters are known at every point of the object:

3 components of the normal strain: ϵ_x, ϵ_y, ϵ_z

3 components of the shearing strain: γ_{xy}, γ_{yz}, γ_{xz}

3 components of the rigid body translation, a_o, b_o, c_o in the directions of x, y, z axes respectively, and

3 components of the rigid body rotations, ω_x, ω_y and ω_z.

In order to calculate the above parameters the displacement field must be approximated by a continuous displacement function (deformation model) $\underline{d}(x,y,z)$ with the three components: $u(x,y,z)$ $v(x,y,z)$ and $w(x,y,z)$ corresponding to the displacements in the x, y and z directions respectively. Usually a polynomial function of an appropriate order is selected as the deformation model depending on how complex is the expected deformation.

Since many deformation models may be fitted to the same set of the observed displacements, the choice of the "best" model is extremely important.

In the so-called Generalized Approach which has recently been developed at the University of New Brunswick (Chrzanowski et al., 1982, Chrzanowski et al., 1983 and Chen, 1983) the choice of the "best" model is based on:

i) an a priori knowledge, either actual or assumed, of the behaviour of the deformable object;

ii) a demonstrated deformation trend determined for instance through an examination of the differenes of observed (or derived and invariant) quantities and an examination of displacements.

iii) global statistical tests and examination of residuals and calculated significance levels of the deformation parameters obtained through the process of fitting.

Thus, generally, the approach consists of three basic processes:

1. Identification of the deformation model;
2. Estimation of the deformation parameters;
3. Diagnostic checking of the deformation models and the final selection of the "best" model.

If more than one "best" model would pass the statistical tests then the model with the fewest unknown deformation parameters should be chosen. The sucess of the proper fitting of a deformation model depends to a large extent on how good our knowledge is on the accuracy of the observed quantities and how many degrees of freedom (redundant observables) we have in the least squares fitting of the model.

A detailed evaluation and theoretical foundations of the generalized approach are given in (Chen, 1983).

Once the parameters of the deformation model are determined the aforementioned basic deformation parameters can easily be calculated from the well known infinitesimal strain-displacement relationships. For instance, if the components u(x,y,z), v(x,y,z) and w(x,y,z) of the displacement function which represents the deformation model are already known then we can calculate at any point (x,y,z):

$$\epsilon_x = \frac{\partial u}{\partial x}, \quad \epsilon_y = \frac{\partial v}{\partial y}, \quad \gamma_{xy} = (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y})$$

$$\omega_x = \frac{1}{2}(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}) \quad \text{etc.}$$

Tilts in the vertical plane around axes x and y will be calculated from:

$$\tau_x = \frac{\partial w}{\partial y} \qquad \text{and} \qquad \tau_y = \frac{\partial w}{\partial x} \qquad \text{respectively}$$

The latter calculation may be usefuul when using tiltmeters in monitoring surveys as it is the case in the Sparwood project.

The integrated evaluation of the ground surveys, photogrammetry and tilt measurements in the test area using the generalized approach has been beyond the scope of this report. Nevertheless some results are given to illustrate the geometrical analysis.

Table 6.1 lists the coordinates and displacements of ground markers (Fig. 6.2) obtained from geodetic surveys (performed by Westar Mining) for the period October 1980 to August 1982.

The following displacement function has been fitted to the given displacements:

$$dx_i = u(x_i y_i) = a_o + a_1 x_i + a_2 y_i + a_3 xy + a_y a x_i^2 + a_5 y_i^2 + a_6 x_i^2 + a_7 x_i y_i^2$$
$$dy_i = v(x_i y_i) = b_o + b_1 x_i + b_2 y_i + b_3 x_i y_i + b_4 x_i^2 + b_5 y_i^2 + b_6 x_i^2 + b_7 x_i y_i^2$$
$$dz_i = w(x_i y_i) = c_o + c_1 x_i + c_2 y_i + c_3 x_i y_i + c_4 x_i^2 + c_5 y_i^2 + c_6 x_i^2 + c_7 x_i y_i^2$$

The above mathematical model can be written in a short matrix form:

$$\underline{d} = B\underline{a}$$

Since in the example there were 48 observed displacements and the displacement functions had a total of 24 unknown parameters in the vector $\underline{a}$, the estimation of the vector $\underline{a}$ and its variance-covariance matrix C_d could be performed through the least squares solution:

$$\hat{\underline{a}} = (B^T C_d^{-1} B)^{-1} B^T C_d^{-1} \underline{d} \quad \text{and} \quad C_a = \hat{\sigma}_o^2 (B^T C_d^{-1} B)^{-1}$$

where $\hat{\sigma}_o^2$ is the estimated variance factor (variance of the observation with unit weight) and C_d is the variance-covariance matrix of the observations (in this case, displacements).

Due to a lack of information from Westar Mining on the accuracy of the determination of the displacements the matrix C_d has been assumed to be diagonal (no correlation between the displacements) with the same variances $\sigma_d^2 = (0.05 \text{ m})^2$ for each displacement components dx_i, dy_i, dz_i.

For computational reasons, all the coordinates in the above alculations were reduced by subtracting in Table 6.1 the coordinates of station 1 from all other coordinates.

Table 6.2 gives the solution vector $\hat{\underline{a}}$ (estimated parameters of the deformation model) with their probabilities (confidence levels $1-\alpha$). As one can see, most of the parameters of the deformation model in the x direction (parameters a_0, a_1 ... etc.) and all the parameters of the component $\underline{d}z$ of the displacement function are very significant with the probabilities larger than 0.95 (>95%). Fitting in the y direction would perhaps require a different model because the parameters b_i have small

Table 6.1. Coordinates and Displacements (1980-1982) of the Survey Stations.

		Reduced		Reduced
STATION	E/X	X	N/Y	Y
1	1683.980	0.000	1228.280	0.000
2	1636.220	-47.760	1188.040	-40.240
4	1541.360	-142.620	1080.340	-147.940
5	1439.230	-244.750	1017.130	-211.150
A1	1610.760	-73.220	1345.010	116.730
A2	1564.760	-119.220	1300.190	71.910
A3	1488.250	-195.730	1218.790	-9.490
A4	1420.360	-263.620	1143.030	-85.250
A5	1379.910	-304.070	1099.520	-128.760
B1	1564.640	-119.340	1300.290	72.010
B4	1353.160	-330.820	1333.010	104.730
T0	1669.140	-14.840	1285.950	57.670
T1	1729.860	45.880	1275.500	47.220
T2	1585.110	-98.870	1324.730	96.450
T3	1559.870	-124.110	1432.820	204.540
T4	1631.780	-52.200	1205.880	-22.400

DISPLACEMENT COMPONENTS :

STATION	DX	σ_d	DY	σ_d	CZ	σ_d
1	-0.870	0.050	-0.100	0.050	-0.390	0.050
2	-0.959	0.050	-0.170	0.050	-0.910	0.050
4	-1.370	0.050	-0.470	0.050	-1.310	0.050
5	-1.410	0.050	-0.380	0.050	-1.730	0.050
A1	-1.420	0.050	-0.150	0.050	-1.600	0.050
A2	-1.610	0.050	-0.420	0.050	-1.770	0.050
A3	-1.660	0.050	-0.450	0.050	-1.350	0.050
A4	-1.440	0.050	-0.650	0.050	-1.550	0.050
A5	-0.770	0.050	-0.660	0.050	-0.390	0.050
B1	-1.510	0.050	-0.510	0.050	-1.760	0.050
B4	-1.960	0.050	-0.670	0.050	-2.100	0.050
T0	-1.230	0.050	-0.150	0.050	-1.000	0.050
T1	-1.120	0.050	-0.050	0.050	-0.610	0.050
T2	-1.760	0.050	-0.460	0.050	-1.870	0.050
T3	-1.720	0.050	-0.460	0.050	-1.420	0.050
T4	-1.070	0.050	-0.280	0.050	-0.990	0.050

Table 6.2. Parameters of the Deformation Model.

```
  ESTIMATED DEFORMATION COMPONENTS AND "(1-ALPHA)" LEVELS

        A0      -0.8357183654D 00            1.0000

        U0      -0.1295421783D 00            0.8345
-----------------------------------------------------------
        C0      -0.6621916413D 00            1.0000

        A1       0.7983852685D-02            1.0000

        A2      -0.8377725905D-02            0.9996
-----------------------------------------------------------
        A3      -0.8922092140D-04            0.9993

        A4       0.2086132641D-04            0.9997
-----------------------------------------------------------
        A5       0.8957108585D-05            0.5425

        A6      -0.2535019090D-06            0.9998

        A7       0.5531293456D-07            0.9963
-----------------------------------------------------------
        B1       0.1885905459D-02            0.7996

        B2       0.7317736632D-03            0.2754

        B3       0.1228652919D-04            0.4016
-----------------------------------------------------------
        B4      -0.1505344027D-05            0.2398

        B5      -0.6976138644D-05            0.5419
-----------------------------------------------------------
        B6       0.4035431244D-07            0.5094

        B7      -0.6380431789D-07            0.6634

        C1       0.1389095155D-01            1.0000
-----------------------------------------------------------
        C2      -0.1226835777D-01            1.0000
-----------------------------------------------------------
        C3      -0.1379275687D-03            1.0000

        C4       0.4083076796D-04            1.0000

        C5       0.4585427022D-04            0.9991
-----------------------------------------------------------
        C6      -0.3980190186D-06            1.0000

        C7       0.2334937523D-06            0.9985
-----------------------------------------------------------
```

Table 6.3. Residuals and the Global Statistical Test.

```
VECTOR OF ACTUAL RESIDUALS          STANDARDIZED RESIDUALS :

 (#    2)         1                  (#    3)         1

   1   3.0292D-02                      1      0.17663
   2  -2.9542D-02                      2     -0.17173
   3      0.22781                      3      1.32429
   4  -2.4233D-02                      4     -0.14143
   5  -7.2185D-02                      5     -0.42127
   6  -1.6876D-03                      6  -9.8492D-03
   7  -4.0048D-02                      7     -0.20310
   8   7.3121D-02                      8      0.37383
   9     -0.13460                      9     -0.68262
  10   2.7947D-02                     10      0.13683

  11  -3.5239D-02                     11     -0.17211
  12   9.2189D-02                     12      0.45036
  13     -0.19905                     13     -1.20679
  14     -0.13869                     14     -0.84079
  15   1.4839D-02                     15   8.9561D-02
  16   3.0739D-02                     16      0.18969
  17   2.5677D-02                     17      0.15795
  18   1.1116D-02                     18   6.8378D-02
  19   6.2583D-02                     19      0.37966
  20     -0.10482                     20     -0.62951

  21      0.13875                     21      0.63353
  22      0.11572                     22      0.66660
  23  -9.6527D-03                     23  -5.5955D-02
  24      0.25672                     24      1.47752
  25  -9.4775D-02                     25     -0.46901
  26   3.7066D-02                     26      0.19125
  27     -0.22740                     27     -1.17331
  28  -6.9507D-02                     28     -0.42756
  29      0.11539                     29      0.70979
  30   9.3524D-04                     30   5.7529D-03

  31  -3.1638D-02                     31     -0.15361
  32  -1.6361D-03                     32  -7.9439D-03
  33  -4.4685D-02                     33     -0.21404
  34     -0.10642                     34     -0.64831
  35  -2.3657D-03                     35  -1.4412D-02
  36     -0.23589                     36     -1.43710
  37      0.10213                     37      0.53728
  38   4.2457D-02                     38      0.22336
  39   7.8597D-02                     39      0.41349
  40      0.17144                     40      1.07580

  41   9.5928D-02                     41      0.60189
  42     -0.10917                     42     -0.68495
  43   5.2597D-02                     43      0.26162
  44  -6.1089D-03                     44  -3.0386D-02
  45   6.3105D-02                     45      0.31389
  46  -2.7756D-02                     46     -0.16956
  47   1.0591D-02                     47   6.4656D-02
  48     -0.13125                     48     -0.80181


ESTIMATED VARIANCE FACTOR :      0.5564571664

 DEGREES OF FREEDOM :   24

  CHI SQUARED TEST AT 0.05 :      5.2147  <  1.0  <    15.5649  ?

  CHI SQUARED TEST AT 0.01 :      4.5936  <  1.0  <    20.8081  ?
```

significance levels.

Table 6.3 lists results of the global test on the estimated variance factor (χ^2 test) and the residuals of the displacements. The test on the variance factor ($\hat{\sigma}_o^2 = 8.56$) failed indicating that either the selected deformation model was wrong or the assumed accuracies of the displacements were in fact too large by a factor of $\sqrt{\hat{\sigma}_o^2} = 2.93$. It means that the actual accuracies were about 0.15 m. The residuals in the Table 6.3 reached values up to 0.26 m.

The obtained deformation model has been used to compare the observed tilts (Oct. 1980 - August 1982 in Table 2.1) at the stations T-1, T-3 and T-4 (tilt measurements at T-2 were interrupted in 1981 and they could not be compared) with the calculated $\tau_x(B+)$ and $\tau_y(A+)$. The result of the comparison are shown in Table 6.4.

Table 6.4 Comparison of the observed and calculated (from the deformation model) tilts (1980-1982).

Station	Sensor	Observed	Calculated	σ_τ
T-1	A+	2077"	2050"	±331"
	B+	754"	2918"	±658"
T-3	A+	2588"	1155"	±630"
	B+	1248"	1082"	±363"
T-4	A+	1474"	2454"	±260"
	B+	1105"	1577"	±275"

As one can see, the standard deviations of tilts calculated from the geodetic survey through through the least square approximation of the displacement field are very large in comparison with the accuracy of tilt measurements (estimated at $\sigma = 30''$). In 3 cases (3 sensors out of 6) the differrences between the calculated and observed tilts are within the 2σ error. Three other tilts exceeded the confidence interval. There are several possible explanations of the large differences. It is possible that due to the discontinuities (cracks) in the rock masses reaching the surface, the tiltmeter stations could be subjected to local movements of rock blocks. Another explanation is that the distribution of the survey points in respect to the tiltmeters (all the points are on one side of the array of tiltmeters) is not favourable for the approximation of the displacement field at the locations of the tiltmeters. More research is needed. Nevertheless, the given example demonstrates the method of the generalized approach into an integrated analysis of different types of observables.

If only an array of tiltmeters would be used in monitoring the ground subsidence than the component $dz = w(x,y,z)$ of the displacement function (the selected deformation model) could be determined from the aforementioned relationship between the measured tilts and the selected deformation model:

$$\tau_x = \frac{\partial}{\partial y} w(x,y,z) \quad \text{and} \quad \tau_y = \frac{\partial}{\partial x} w(x,y,z) .$$

Of course, in order to be able to determine the unknown parameters of $w(x,y,z)$ through the least squares fitting, there should be more tilt observations than the number of the parameters. In the case of the

Sparwood test the small number of tiltmeters clustered close together would not give any representative model of the actual deformation.

It would be interesting, in the future, to apply the generalized approach to a simultaneous evaluation of the deformation from the ground surveys, photogrammetry and tilt measurements. Such an integration, would require a proper design of the distribution of the survey stations in order to obtain a meaningful deformation model.

7. CONCLUSIONS AND RECOMMENDATIONS

With the details provided in the previous chapters, it can be stated that the requirements of the contract - except for the installation of the new system, which was postponed to August 1984 - have not only been met, but have been exceeded, especially in research.

Even though the original system performed satisfactorily, the maintenance did not only cover routine matters but included improvements to the telemetry system to make it more reliable. An even better performance can be expected.

The observed tilts were evaluated and proved their usefulness for monitoring ground movements. The expansion of the system included a new Master station plus three field stations with Slaves and bi-axial tiltmeters. Master and Slaves have all the improvements incorporated which resulted from the research.

The research concentrated on three areas, namely hardware and software design for the system, the utilization of photogrammetry, and integration and modelling of the different observed quantities for subsidence prediction.

In addition to numerous hardware and software improvements, the new Master incorporates remote control via telephone hook-up. An alarm feature which can be triggered by any Slave has also been developed which permits, recording events whenever they happen. A number of photogrammetric approaches have been investigated. This resulted in the development of a cross-identification method for photographs of different epochs and the computation of movement vectors in model space which subsequently can be oriented for whichever epoch has better ground control values.

A combination of the different types of data (geometric as well as rock mechanics data) has been successfully carried out, and the methodology for integration is given in the report. Although this provides some insight into what has been happening with the subsidence, the actual prediction was most successful when using the finite element approach. The latter research exceeded the scope of this contract, is however included for completeness' sake.

Based on these results, the Consultants recommend that measurements with all three methods (ground surveying, aerial photogrammetry, and tiltmeter readings via telemetry) be continued and expanded if desired and considered a combined method for subsidence monitoring. Further tests and research is required in the actual integration of these diverse measurements into one model. Research on subsidence prediction in such inhospitable areas needs to continue with special emphasis on numerical deterministic modelling, using the finite element method, where the present results have been most encouraging.

REFERENCES

Budryk, W. and S. Knothe (1953). "Einfluss des Untertageabbaus auf die Erdoberflache vom Geisichtspunkt der Sicherung der Objekte." Bergakademie, 5: 59-62.

Chen, Y.Q. (1983). "Analysis of deformation surveys--A generalized approach." Ph.D. dissertation, Department of Surveying Engineering Technical Report 94, University of New Brunswick, Fredericton, N.B.

Chrzanowski, A. and W. Faig (1982). "Ground subsidence determination in mining areas. The Indian Mining and Engineering Journal, Vol. XXI, Nos. 2 and 3, pp. 7-12.

Chrzanowski, A. and M.Y. Fisekci (1982). "Application of tiltmeters with a remote data acquisition in monitoring mining subsidence." Proceedings of the 4th Canadian Symposium on Mining Surveying and Deformation Surveys, Banff, June, pp. 321-333.

Chrzanowski, A. and F. Hart (1983). "Role of the surveyor in North America in studies of ground movements in mining area." Proceedings of the ACSM Annual Convention, Washington, D.C., pp. 262-271.

Chrzanowski, A., Y.Q. Chen and J. Secord (1982a). "A general approach to the interpretation of deformation measurements." Proceedings of the Centennial Meeting of CIS, Ottawa, April, Vol. 2, pp. 247-266.

Chrzanowski, A., Y.Q. Chen and J.M. Secord (1982b). "On the analysis of deformation surveys." Proceedings of the 4th Canadian Symposium on Mining Surveying and Deformation Surveys, Banff, June, pp. 431-452.

Chrzanowski, A., Y.Q. Chen and J. Secord (1983). "On the strain analysis of tectonic movements using fault crossing geodetic surveys." Tectonophysics, Vol. 97, pp. 297-315.

Chrzanowski, A., Y.Q. Chen and A. Szostak-Chrzanowski (1983). "Use of the finite element method in the design and analysis of deformation measurements. Proceedings of the FIG XVIII Congress, Sofia, Bulgaria, June, Paper No. 611.1.

Chrzanowski, A., W. Faig, M. Fisekci and B. Kurz (1982). "Telemetric monitoring of ground subsidence over a hydraulic mining operation in the Canadian Rocky Mountains." Proceedings of the 5th International Symposium for Mine Surveying, Varna, Bulgaria, Vol. 3, pp. 249-256.

Chrzanowski, A., W. Faig, B. Kurz and A. Makosinski (1980). "Development, installation and operation of a subsidence monitoring and telemetry system." Report submitted to CANMET, Calgary.

Faig, W. and C. Armenakis (1982). "Subsidence monitoring by photogrammetry." Proceedings of the Fourth Canadian Symposium on Mining Surveying and Deformation Measurements, Banff, June, pp.

Fisekci, M.Y. and A. Chrzanowski (1981). "Some aspects of subsidence monitoring in difficult terrain and climate conditions of Rocky Mountains, western Canada. Proceedings of the Workshop on Surface Subsidence due to Underground Mining, Ed. S. Peng. Morgantown, WV, 30 Nov-2 Dec, University of West Virginia, pp. 182-197.

Fisekci, M.Y., A. Chrzanowski, B.M. Das and G. La Rocque (1981). "Subsidence studies in thick and steep coal seam mining." Proceedings of the First Annual Conference on Ground Control in Mining, Ed. S. Peng. Morgantown, WV, pp.230-238.

Kratzsch, H. (1983). Mining Subsidence Engineering. Springer-Verlag, Berlin, New York.

Moffit, F.H. and E.M. Mikhail (1980). Photogrammetry. 3rd ed., Harper & Row Inc., New York.

Wells, D.E. and E.J. Krakiwsky (1971). "The method of least squares." Department of Surveying Engineering Lecture Notes 18, University of New Brunswick, Fredericton, N.B.